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Proceedings of Geoclutter and Boundary Characterization 2001

Acoustic Interaction with the Seabed, Workshop held at DREA, Canada 2-3 October, 2001

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Defence R&D Canada

Technical Memorandum
DREA TM 2001-185
October 2001

National Defence Défense nationale

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Technical Memorandum

DREA TM-2001-185

October 2001

Editors

Paul C. Hines, Nicholas C. Makris, Charles W. Holland

Approved by

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DRP Chair

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Abstract

In April-May 2001, consecutive sea trials were conducted at two well characterized shallow water sites off of North America's east coast – the Strataform site off the coast of New Jersey and Scotian Shelf off the coast of Nova Scotia. The trials were in support of two distinct but related research programs referred to respectively as GeoClutter and Boundary Characterization.

The focus for GeoClutter is to develop a methodology for identifying and classifying false targets (in the ASW context) present in littoral waters. These false targets typically occur when Low Frequency Active (LFA) sonars measure strong coherent returns from the seabed at locations where bathymetric maps indicate benign bottoms. This frequently occurs in littoral waters where, for example, ancient river channels are overland with soft sediment. The high-frequency systems employed to measure bathymetry are unable to penetrate the seabed so that these complex sub-bottom features go unnoticed.

Boundary Characterization seeks to enhance active sonar design as well as performance prediction capabilities in littoral waters by statistically characterizing the effects of the complex seafloor and sea surface on broadband scattering and propagation of sound. The principal focus of the project is the development of techniques to measure the environmental parameters that control diffuse reverberation in the low kiloHertz band.

For the purpose of experimental efficiency and because there is significant overlap in the objectives of the two programs, several assets and many personnel participated in both trials. To maintain the momentum of the collaboration and focus the data analysis and modeling efforts, a symposium style workshop was held at DREA in October 2001. The focus of this workshop-symposium was to present an overview of the two sea trials as well as present initial measured and modeled results. Preliminary results indicate that (1) littoral water GeoClutter will cause significant false target reports in present and future LFA systems if it is not addressed. This will require a balanced approach combining fundamental at-sea measurements with signal processing techniques aimed at separating Geoclutter from true targets. (2) The Boundary Characterization program is leading to a much better understanding of the seabed and sea surface and their effect on propagation and scattering of sonar signals. This information will be used to validate and improve Rapid Environmental Assessment (REA) techniques and optimize the performance of multistatic active sonar systems by exploiting environmental knowledge.

Representatives from Defence Research Establishment Atlantic (DREA), SACLANT Center, the US Office of Naval Research (ONR), and the Naval Research Laboratory (NRL), Naval Undersea Warfare Center (NUWC), Massachusetts Institute of Technology (MIT), the Pennsylvania St. University Applied Research Laboratory (PSU ARL), the University of Texas, and the University of Colorado contributed oral and written papers. This proceedings contains the papers contributed to the symposium.

Résumé

En avril et mai 2001, des essais en mer consécutifs ont été menés en deux emplacements bien caractérisés en eau peu profonde au large de la côte orientale de l'Amérique du Nord – le site Strataform au large de la côte du New Jersey et la plateau néo-écossais au large de la Nouvelle-Écosse. Ces essais étaient menés à l'appui de deux programmes de recherche distincts mais reliés, respectivement désignés GeoClutter (géo-interférence) et Boundary Characterization (caractérisation des limites).

Le programme GeoClutter vise principalement à élaborer une méthodologie permettant d'identifier et de classer les faux objectifs (dans le contexte de la LASM) présents dans les eaux littorales. Ces faux objectifs se présentent de manière caractéristique lorsque les sonars actifs à basse fréquence (ABF) fournissent de forts échos cohérents du fond marin aux endroits où les cartes bathymétriques indiquent des fonds anodins. Cela se produit fréquemment dans les eaux littorales où, par exemple, des chenaux de cours d'eau anciens sont recouverts par des sédiments meubles. Les systèmes à haute fréquence utilisés en bathymétrie ne peuvent pénétrer le fond marin ce qui fait que ces complexes entités sous le fond passent inaperçues.

Le programme Boundary Characterization vise à améliorer la conception du sonar actif ainsi que son rendement en termes de capacité de prévision dans les eaux littorales par la caractérisation statistique des effets des fonds marins complexes et de la surface de la mer sur la diffusion et la propagation du son dans une large bande de fréquences. Le projet vise principalement à mettre au point des techniques de mesure des paramètres environnementaux régissant la réverbération diffuse dans partie inférieure de l'intervalle des fréquences kilohertziennes.À des fins d'efficacité des expériences et parce qu'il y a un important chevauchement des objectifs des deux programmes, plusieurs membres du personnel ont participé aux deux essais avec les mêmes biens. Afin de maintenir une grande collaboration et de focaliser les efforts d'analyse et de modélisation des données, une atelier du genre symposium a été tenu au CRDA en octobre 2001. Cet atelier-symposium consistait à présenter une vue d'ensemble des deux essais en mer ainsi que les résultats mesurés et modélisés initiaux. Les résultats préliminaires indiquent 1) que la géo-interférence engendrera d'importants rapports de faux objectifs par les actuels et futurs systèmes de LASM si le problème n'est pas étudié; l'étude de ce problème exigera une approche équilibrée combinant des mesures fondamentales en mer avec des techniques de traitement des signaux visant à séparer la géo-interférence des objectifs véritables, et 2) que le programme sur la caractérisation des limites mène à une bien meilleure compréhension du fond marin et de la surface de la mer ainsi que de leur effet sur la propagation et la diffusion des signaux sonores. Cette information sera utilisée pour valider et améliorer les techniques d'évaluation rapide de l'environnement (ÉRE) ainsi que pour optimiser le rendement des systèmes sonars actifs multistatiques en exploitant cette connaissance du milieu.

Des représentants du Centre de recherches pour la défense Atlantique (CRDA), du Centre du SACLANT, de l'Office of Naval Research (ONR) et du Naval Research Laboratory (NRL) des É.-U., du Naval Undersea Warfare Center (NUWC), du Massachusetts Institute of Technology (MIT), de l'Applied Research Laboratory à la Pennsylvania St. University (PSU ARL), de l'Université du Texas et de l'Université du Colorado ont présenté des communications orales et écrites. Ce compte rendu comprend les communications présentées dans le cadre du symposium.

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Executive summary

DREA's Underwater Acoustic section is collaborating with the United States and SACLANCEN on two distinct but related research programs. The programs are referred to as GeoClutter and Boundary Characterization, respectively. In April-May 2001, consecutive sea trials were conducted at two well characterized shallow water sites off of North America's east coast. For the purpose of experimental efficiency and because there is significant overlap in the objectives of the two programs, several assets and personnel participated in both trials. To maintain the momentum of the collaboration and focus the data analysis and modeling efforts, a symposium style workshop was held at DREA in October 2001. Representatives from DREA, SACLANT, ONR, and NRL as well as several universities contributed oral and written papers. This proceedings contains the papers contributed to that symposium.

The focus for GeoClutter is to develop a methodology for identifying and classifying false targets (in the ASW context) present in littoral waters. These false targets typically occur when Low Frequency Active (LFA) sonars measure strong coherent returns from the seabed at locations where bathymetry maps indicate benign bottoms. This frequently occurs in littoral waters where, for example, ancient river channels are overlaid with soft sediment. The high-frequency systems employed to measure bathymetry are unable to penetrate the seabed so that these complex sub-bottom features go unnoticed.

Boundary Characterization seeks to enhance active sonar design as well as performance prediction capabilities in littoral waters by statistically characterizing the effects of the complex seafloor and sea surface on broadband scattering and propagation of sound. The principal focus of the project is the development of techniques to measure the environmental parameters that control diffuse reverberation in the 1-10 kHz band.

The focus of this workshop-symposium was to present an overview of the two sea trials as well as present initial measured and modeled results. Preliminary results indicate that (1) littoral water GeoClutter will cause significant false target reports in present and future LFA systems if it is not addressed. This requires a balanced approach combining fundamental at sea measurements with signal processing techniques aimed at separating Geoclutter from true targets. (2) The Boundary Characterization program is leading to a much better understanding of the seabed and sea surface and their effect on propagation and scattering of sonar signals.

A second GeoClutter sea trial is scheduled for Spring of 2003. Data from the Boundary 2001 sea trial will be used to validate and improve sonar performance models at DREA. This will lead to improved sonar performance prediction models within the fleet.

Hines, Paul C., Makris, Nicholas C., Holland, Charles W. 2001. Proceedings of Geoclutter and Boundary Characterization 2001: Acoustic Interaction with the Seabed, Workshop-Symposium held at DREA, Canada 2-3 October, 2001. DREA TM 2001-185 Defence Research Establishment Atlantic.

Sommaire

La Section de l'acoustique sous-marine du CRDA collabore avec les États-Unis et le SACLANCEN à deux programmes de recherche distincts mais connexes. Ces programmes sont respectivement désignés GeoClutter (géo-interférence) et Boundary Characterization (caractérisation des limites). En avril et mai 2001, des essais en mer consécutifs ont été menés en deux emplacements bien caractérisés en eau peu profonde au large de la côte orientale de l'Amérique du Nord. Pour des raisons d'efficacité des expériences et parce qu'il y a un important chevauchement des objectifs des deux programmes, plusieurs membres du personnel ont participé aux deux essais avec les mêmes biens. Afin de maintenir une grande collaboration et de focaliser les efforts d'analyse et de modélisation des données, une atelier du genre symposium a été tenu au CRDA en octobre 2001. Ces représentants du CRDA, du SACLANT, de l'ONR et du NRL ainsi que de plusieurs universités ont présenté des communications orales et écrites. Ce compte rendu comprend les communications présentées dans le cadre de ce symposium.

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Cet atelier-symposium consistait à présenter une vue d'ensemble des deux essais en mer ainsi que les résultats mesurés et modélisés initiaux. Les résultats préliminaires indiquent 1) que la géo-interférence dans les eaux littorales engendrera d'importants rapports de faux objectifs par les actuels et futurs systèmes ABF si le problème n'est pas étudié, l'étude de ce problème exigera une approche équilibrée combinant des mesures fondamentales en mer avec des techniques de traitement des signaux visant à séparer la géo-interférence des objectifs véritables, et 2) que le programme sur la caractérisation des limites mène à une bien meilleure compréhension du fond marin et de la surface de la mer ainsi que de leur effet sur la propagation et la diffusion des signaux sonores.

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Un deuxième essai GeoClutter en mer est prévu au printemps de 2003. Les données de l'essai en mer Boundary 2001 seront utilisées pour valider et améliorer les modèles de rendement des sonars au CRDA ce qui permettra de produire des modèles améliorés de prévision du rendement du sonar pour la flotte.

Hines, Paul C., Makris, Nicholas C., Holland, Charles W. 2001.. Proceedings of Geoclutter and Boundary Characterization 2001: Acoustic Interaction with the Seabed. Workshop-Symposium held at DREA, Canada 2-3 October. 2001 DREA TM 2001-185. Defence Research Establishment Atlantic.

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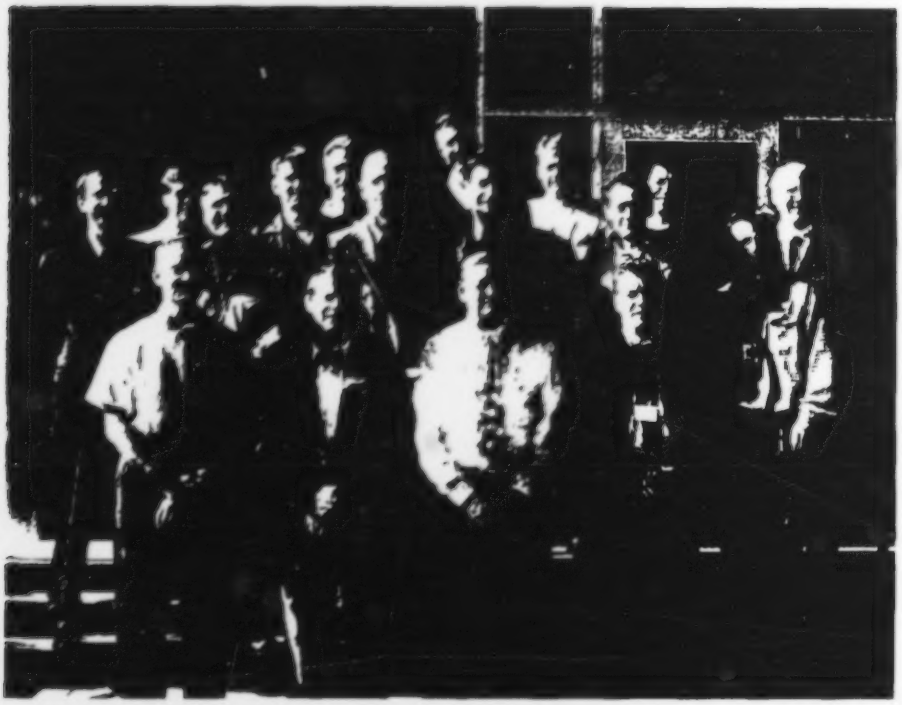

Workshop Attendees

Back Row (left to right) John Preston, Shawn Stewart, Jeff Simmen, Charles Holland, Peter Nielsen, Nick Chotiros, Kevin LePage

Middle Row (left to right) Roger Gauss, John Osler, Mike Sundvik, Richard Katz, Paul Hines, Darcy MacDougald

Front Row (left to right) Dan Hutt, Woody Nero, Dale Ellis, Chris Harrison

Not Shown: Nick Makris, Purnima Ratilal, Doug Abraham, Lillie Ruhlmann

#517148①

High resolution geoacoustic measurements on the New Jersey and Scotian Shelf

Author: Charles W. Holland, Applied Research Lab, Pennsylvania State University, PO Box 30, State College, PA 16804

Abstract
One of the hallmarks of shallow water ocean environments is spatial variability of the seabed structure. New local (short-range) techniques were employed in the STRATAFORM and Scotian shelf areas in order to develop high resolution physical properties of the seafloor and sub-bottom layering. The results from the analyses will provide data to validate long-range techniques, i.e., the Rapid Environmental Assessment (REA) techniques. In addition, the data are expected to provide new insight into a variety of shallow water sediments including extreme end members: very fine-grained and very coarse-grained sediments. [work supported by NATO SACLANT Undersea Research Centre]

1. Introduction

The weakest link in performance prediction for naval systems operating in coastal regions is the environmental data that drive the models. In shallow water downward refracting environments, the seabed properties and morphology often are the controlling environmental factors. The Boundary 2001 Experiment conducted measurements of seafloor reflection, scattering, propagation, reverberation, and ambient noise in order to validate and refine Rapid Environmental Assessment (REA) methods and develop high-resolution scientific measurement techniques.

This paper contains an overview of the seafloor reflection and scattering measurements and a preliminary look at representative data. The objectives of the measurements were to provide self-consistent high resolution geoacoustic properties of the seabed. By self-consistent, it is meant a unified set of seabed properties that can predict both the reflection and the scattering.

2. Seabed reflection measurements

The seabed reflection technique was developed in order to extract very high resolution geoacoustic information from the seafloor in shallow water. It is a "local" technique in the sense that it samples a relatively small (a few hundred meters) region of the seafloor. This local attribute creates the ability to develop range-dependent geoacoustic models by making measurements at several sites. Local seabed reflection measurements were conducted in a variety of locations in the STRATAFORM area (New Jersey shelf) and Scotian Shelf as shown in Figure 1.

The source employed in the experiments was a Geoacoustics Model 5813B Boomer mounted on a catamaran at a nominal depth of 0.40 m. Usable bandwidth from this source is quite large, from ~300 – 10000 Hz, the source repetition rate was 1 pulse per second. The receiver consisted of a vertical array of 4 hydrophones spaced at 10m. Data were sampled at 48 kHz with a low pass filter of 20 kHz and telemetered back to R/V Alliance.

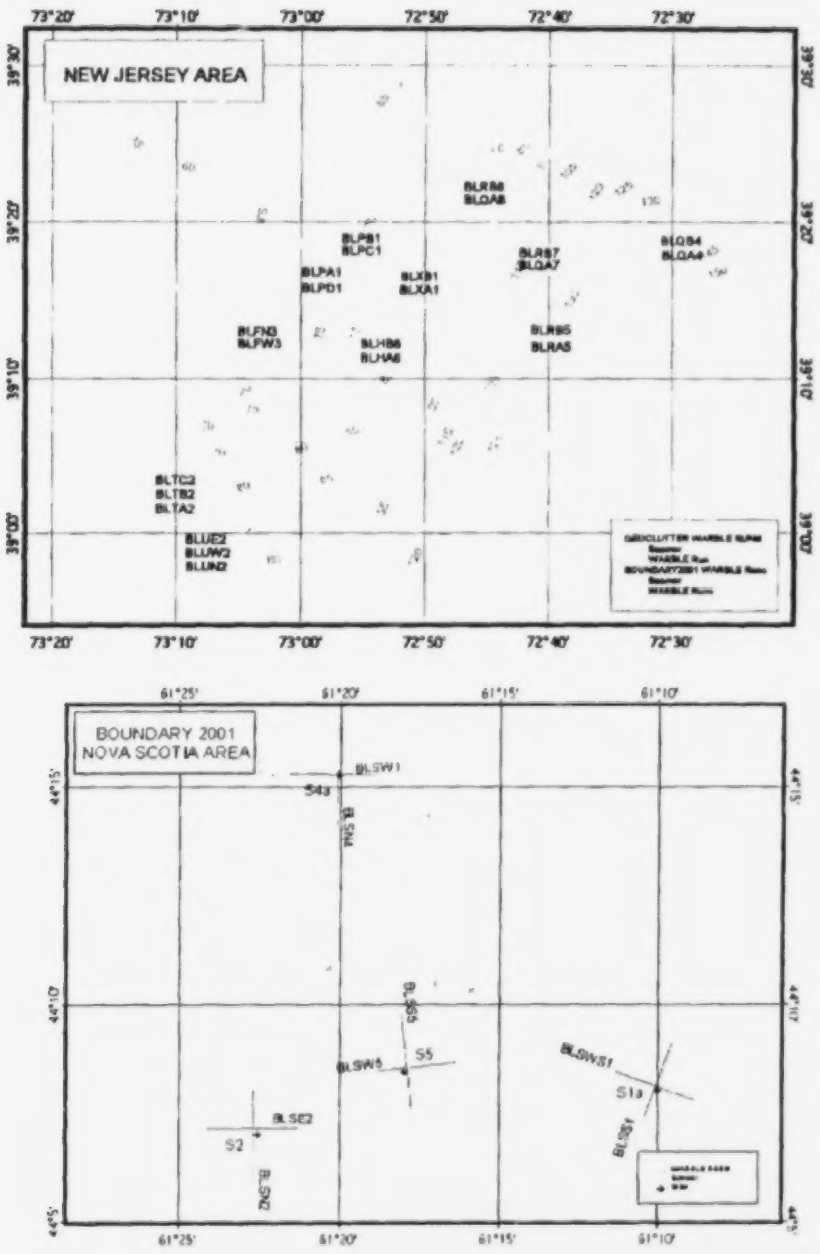

Figure 1 Location of seabed reflection measurements on the New Jersey shelf (depth in meters) and Scotian shelf (depth in fathoms).

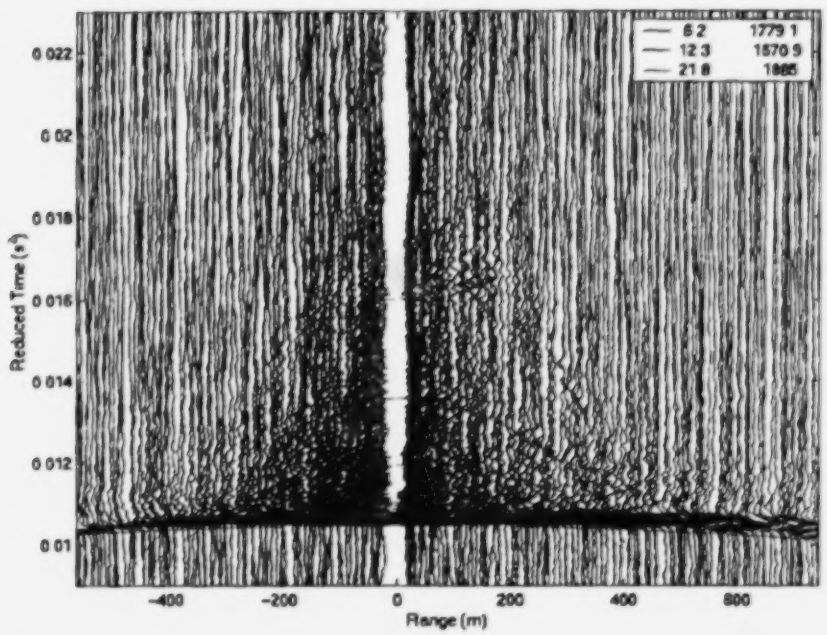

Figure 2. Raw time series data at Site N5 with fitted hyperbolae (red lines). Preliminary layer thicknesses and interval velocities are shown in the legend.

Raw reflection time series at Site N5 (BLRA5 on Figure 1), are shown in Figure 2 (data were decimated to every 4th ping). Range is referenced to the location of the receiver; the time axis has been mapped by a hyperbolic function to "flatten" the seabed reflected arrival, which is apparent at 0.01 s^2. A time domain technique was used as described in Holland and Osler (2000) to obtain the initial estimate of the sound speed structure in the sediment. The red lines show fits to the sub-bottom arrivals and the resulting interval velocities are shown in the legend. The uppermost layer of sediment at N5 has a very high impedance and attenuation. In addition there is a substantial amount of scattering, manifest by the long incoherent tail following the reflection from the water-sediment interface. These characteristics tend to mask the details of the arrival structure.

The data shown in Figure 2 were processed to obtain the bottom reflection loss as a function of angle and frequency, shown in Figure 3a and 3b. One of the salient features of the data is that the critical angle is frequency dependent, and inversely proportional to frequency. This implies that propagation loss will be smallest at low frequencies Also shown in Figure 3 (c,d) are the bottom reflection loss data from BLQA4 (Site N4). The low angle (less than 30 degree) data show greater loss than at Site N5. This is due to the lower impedance sediment at Site N4, very rough estimates for interface sound speed and density are 1510 m/s and 1.7 g/cc. The complex behavior of the reflection coefficient at low angles is almost certainly due to layering.

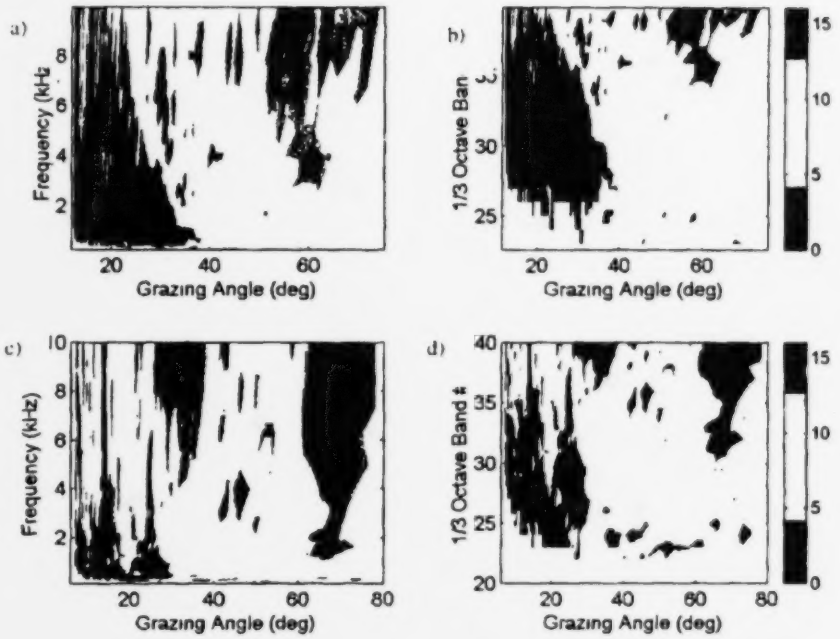

Figure 3. Comparison of measured reflection loss (dB) at Sites N5 (a,b,) and Site N4 (c,d). The data are presented in both linear frequency and log frequency (1/3 octave band #s 20, 30,40 correspond to 100, 1000,10000 Hz respectively). Note the frequency dependence of the critical angle at Site 5, which is probably due to sediment sound speed gradients and/or layering Note that the low angle (less than 30 degrees) reflection coefficient is significantly larger at Site 4 leading to larger transmission losses than at Site 5.

Figure 4 compares a simple half-space model reflection loss prediction (red line) with the measured data at Site N5. The sound speed was derived from time-domain measurements (see Figure 2) and the density from the high-angle reflection loss at low frequency. If the sediment could be treated as a half-space, the reflection coefficient would be frequency independent. The model-data comparison serves to indicate that at many frequencies a half-space approximation is inappropriate. The frequency dependence of the reflection loss is in large measure due to fine-scale layering. Layering is indeed observed on the seismic reflection data at this site. Future modeling will incorporate the layering structure using these features to extract information about the sediment structure.

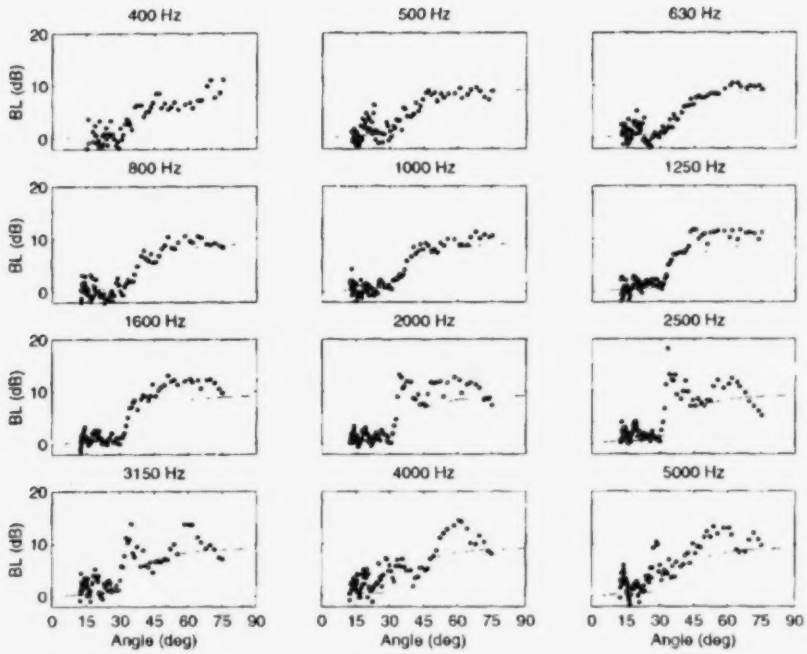

Figure 4. Measured reflection loss at Site N5 along with half-space model predictions 1780 m/s; 1.8 g/cc; 0.5 dB/m/kHz. The sound speed was derived from time-domain measurements (see Figure 3) and the density from the high-angle reflection loss at low frequency. Sediment layering is obviously present which gives rise to the frequency dependence of the reflection loss.

3. Seabed Scattering

The principal advantage of the direct path scattering measurement technique is that many of the assumptions that plague extraction of scattering strength from reverberation data are eliminated, so that the frequency and angular dependence of bottom scatter can be studied more precisely. Thus, the direct path measurements can be used to examine the validity of the assumptions employed in the REA reverberation method.

Details of the direct path technique are described in Holland et al. (2000). The technique allows not only measurement of bottom scattering but also can directly provide information on the scattering mechanism (i.e., interface or sub-bottom volume scattering). Knowledge of the scattering mechanism is important because it is believed to be an important key for predicting the frequency dependence of the scattering. Measurement locations in the STRATAFORM area and Scotian shelf area are shown in Figure 5. The locations correspond to the locations of the reflection measurements.

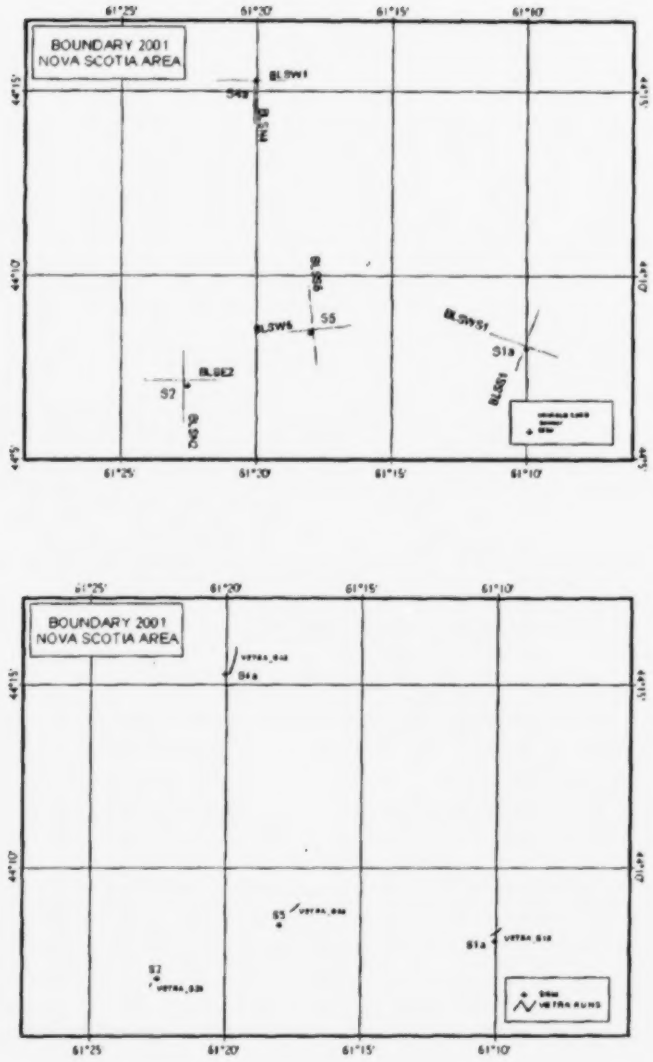

Figure 5. Location of seabed scattering measurements in the STRATAFORM area (New Jersey shelf, depth in meters) and on the Scotian shelf (depth in fathoms).

Beam time series data from the scattering experiment at various sites are shown in Figure 6. The receiver was a 96 element volumetric array, configured in 3 parallel planar, horizontally-oriented, star patterns of 32 elements each. The array was steered to the

horizontal. Though scattering strength has not yet been extracted from these (or the vertical array) data, it is clear that there is a rich diversity in scattering statistics as a function of geographic position. The analyses will attempt to describe that variability in terms of the underlying physical properties.

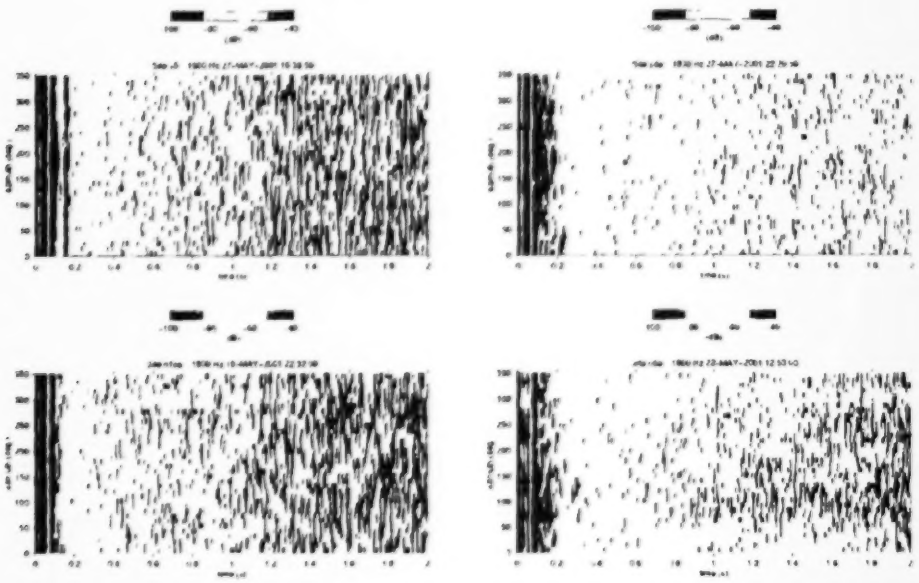

Figure 6. Normalized received level from a horizontal planar array at 1800 Hz. 0 degrees is north. The sites on the Scotian shelf are: a) Site S5 sandy gravel 110 m water depth; b) Site S4a sandy gravel over tertiary bedrock, 95 m water depth; and on the New Jersey: c) Site N1A, sand over buried river channels 80 m water depth and d) Site N6 sand, 86m water depth.

4. Supporting Environmental Data

A considerable amount of supporting oceanographic and geophysical data were collected. Selected data are shown here, the data set will be distributed on a CD-ROM [Holland et al. (2001)]

A summary of the CTD/XBT data from the New Jersey Shelf is shown in Figure 7. Dale Ellis (pers. comm.) noted that a significant part of the observed variability appeared to be due to spatial rather temporal variability. Temporal variability ostensibly was dominated by the interaction of the Gulf Stream with the Labrador Current. Figure 8 shows satellite SST image on May 11 (images for the rest of the cruise are available on the CD-ROM). A summary of the CTD/XBT data from the Scotian shelf is shown in Figure 9, where the variability was substantially smaller.

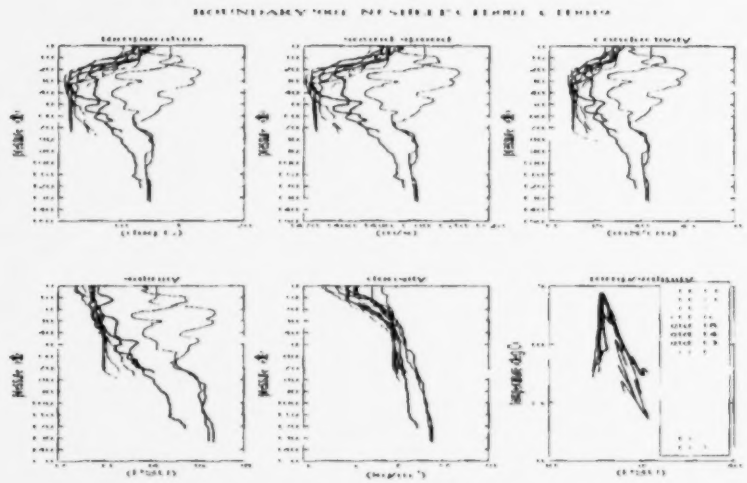

Figure 7. Summary of CTD data collected during the first phase of the experiment (New Jersey shelf).

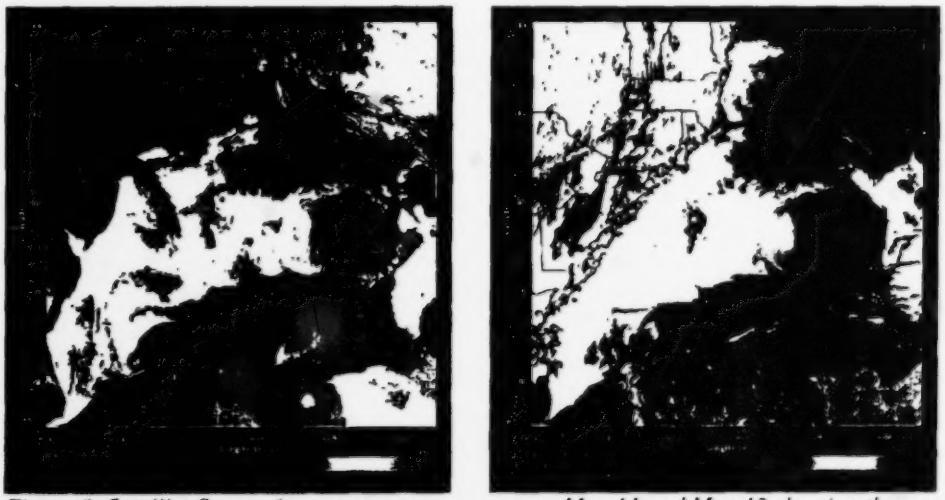

Figure 8. Satellite Sea surface temperature images on May 11 and May 12 showing the warm Gulf Stream and eddies Our operating area is roughly bounded by 39 00N 73 15 W and 39 30N 72 30W

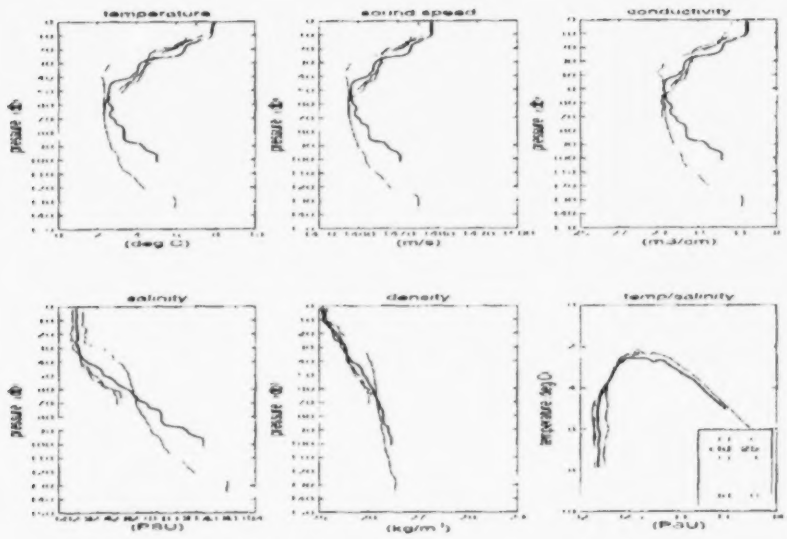

Figure 9. Summary of CTD data collected during the second phase of the experiment (Scotian shelf)

5. Summary

An overview of the seabed reflection and scattering measurements collected during Boundary 2001 was provided, along with brief and preliminary results at several sites The data collected provide a very promising basis from which to meet the analyses objectives, i.e., to develop high-resolution geoacoustic models describing sediment deterministic and stochastic properties and to use that information to validate REA techniques.

6. References

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4517149(2)

Self-Consistent Measurements of Seabed Reflection and Scattering in the STRATAFORM Area

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Abstract
The principal objective of the recent GeoClutter Experiment was to determine the physical mechanisms that give rise to geological clutter from low frequency (~400 Hz) active sonar pulses. In order to determine sub-bottom mechanisms and quantify their effect, measurements of the sediment physical properties are required. Deterministic and stochastic sediment properties can be obtained from recently developed local seabed reflection and scattering measurement techniques. Preliminary results from these measurements are provided and discussed. Reverberation measurements at 1800 Hz received on a volumetric array also show clutter-like events. [work supported by NATO SACLANT Undersea Research Centre]

1. Introduction

Two important acoustic parameters for predicting acoustic interaction with the seabed are bottom reflection and bottom scattering strength. Historically, seabed reflection and scattering have been treated in a disconnected fashion both in measurement and analysis. A coupled approach to reflection and scattering was conducted during the GeoClutter and Boundary2001 Experiments. By coupled, it is meant that the reflection and scattering measurements are not only co-located, but sample commensurate spatial scales of the seabed. It is also meant that the processing and analyses employ commensurate assumptions and modeling. This short paper contains an overview of the seabed reflection and scattering measurements and very preliminary results.

2. Seabed reflection

The seabed reflection technique was developed in order to extract very high resolution geoacoustic information from the seabed. It is a "local" technique in the sense that it samples a relatively small (a few hundred meters) region of the seabed. This local attribute creates the opportunity to develop range-dependent geoacoustic models by making measurements at several sites [see Holland (2000)]. Local (short-range) seabed reflection measurements were conducted in a variety of locations in the STRATAFORM area (see Figure 1). The objective of these experiments was to measure quantitative properties of the sediment, which are required for modeling monostatic/bistatic reverberation and determining the scattering mechanism.

The source employed in the experiments was a Geoacoustics Model 5813B Boomer mounted on a catamaran at a nominal depth of 0.40 m. Usable bandwidth from this source is quite large, from ~300 – 10000 Hz; the source repetition rate was 1 pulse per second. The receiver consisted of a vertical array of 4 hydrophones of which only one hydrophone (~25 meters above the bottom) was employed in the analysis. Data were sampled at 48 kHz with a low pass filter of 20 kHz and telemetered back to R/V Alliance.

Figure 2 shows the raw time series of the reflection data at BLUW2 near Site N2, decimated to show every 3rd ping. The location of this reflection measurement was chosen because it lay directly along a southwesterly trending line where bi-static clutter events were observed during the experiment. Range is referenced to the location of the receiver, the time axis has been mapped by a hyperbolic function to "flatten" the seabed reflected path, which arrives at .005 s^2; the direct path arrives at 0.0013 s^2.

A time domain technique was used as described in Holland and Osler (2000) to obtain the initial estimate of the sound speed structure in the sediment. The red hyperbolae in Figure 2 are the fits to sub-bottom arrivals; the resulting interval velocities given in the legend and displayed in Figure 3. The initial results indicate a sandy sediment with an intercalating layer of gravel. The top of the gravel layer is probably the 'R' reflector, although the base of the gravel layer appears to have a substantial scattering cross-section. There is almost certainly a strong sound speed gradient in the upper layer, but the time domain is not capable of resolving it. Frequency domain analysis (reflection coefficient) will be conducted to refine the sound speed estimates and extract gradient information. Also shown in Figure 3 are seismic reflection data that show the lateral variability of the sand and gravel layers.

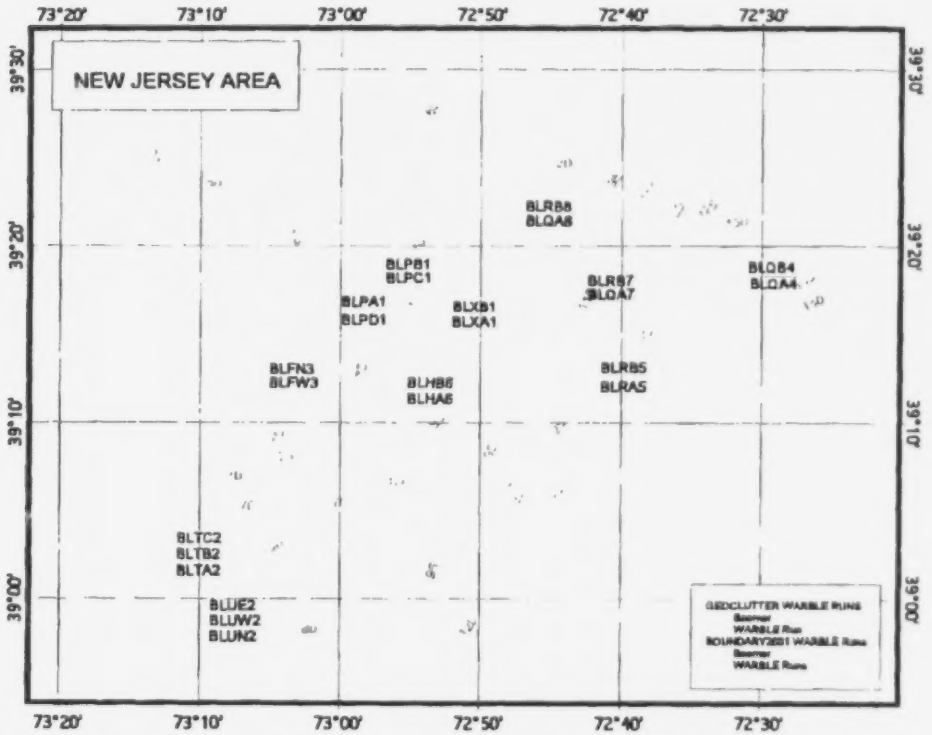

Figure 1. Location of seabed reflection measurements in the STRATAFORM area (New Jersey Shelf).

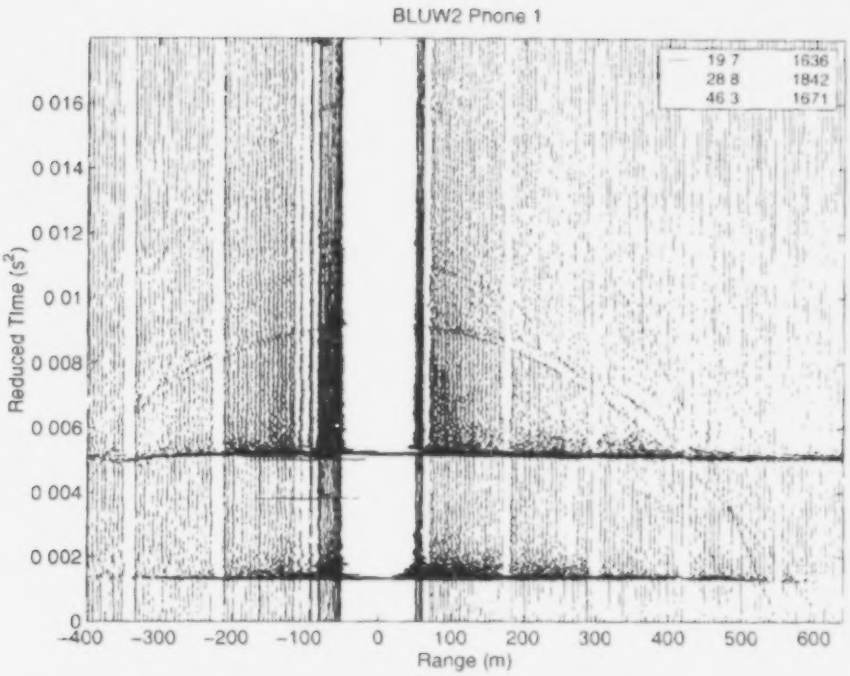

Figure 2 Raw time series data near Site N2 with fitted hyperbolae (red lines). Preliminary layer thicknesses and interval velocities are shown in the legend. The base of the first layer is believed to be the "R" reflector

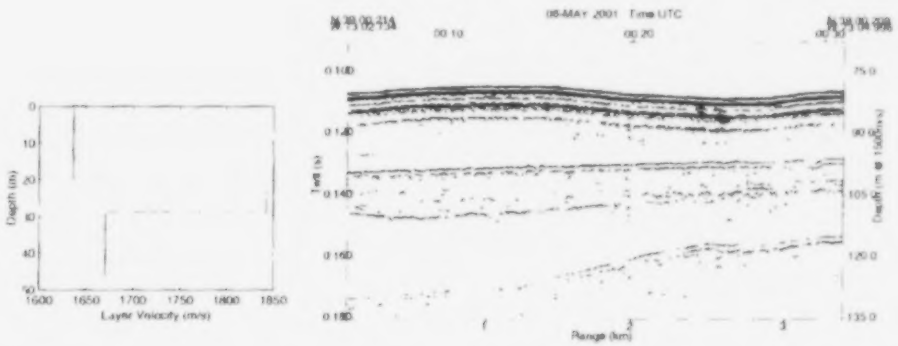

Figure 3. Preliminary interval velocities from Site N2 based on the analysis of data shown in Figure 2 and normal incidence reflection data along the track.

A reflection data of considerable importance are those at Site 1 (BLXA1) where numerous clutter events were observed. Reflection measurements were conducted directly over a buried river channel, both parallel and perpendicular to the main trunk channel. These measurements have not yet been analyzed.

3. Scattering

Details of the technique for the direct path bottom scattering measurements are given in Holland et al (2000). Like the reflection technique, the scattering measurements are "local", i.e., yield scattering strength in a relatively small (several 100 m) radius. The technique allows not only measurement of bottom scattering but also can directly provide information on the scattering mechanism (i.e., interface or sub-bottom volume scattering). Knowledge of the scattering mechanism is important because it is believed to be an important key for predicting the frequency dependence of the scattering. Measurement locations in the STRATAFORM area are shown in Figure 4

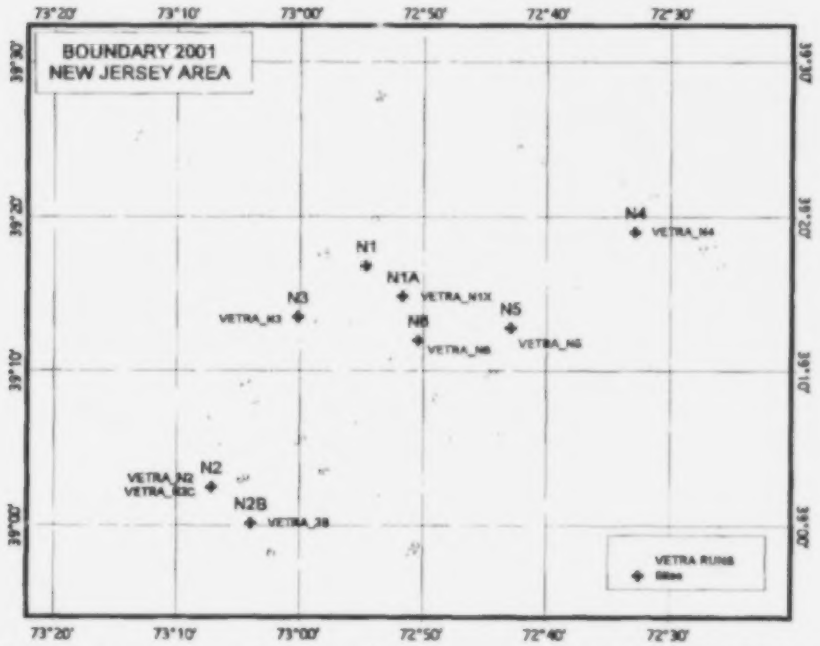

Figure 4. Location of seabed scattering measurements in the STRATAFORM area (New Jersey shelf).

Beam time series data at Site N2 received on a quasi-monostatic vertical array are shown in Figure 5. The monostatic bottom scattering branch can be seen starting at 0.04 seconds in beam 22 (near vertical incidence) and rising up to beam 14 (grazing incidence) at 0.2 seconds. Following that main branch there is a smaller arrival that appears to correspond to scattering from the base of the gravel layer. These data (and associated lower frequency data) are expected to be very useful in determining the scattering kernel of the sand and gravel-sand horizons. Data were collected at frequencies from 600- 3600 Hz.

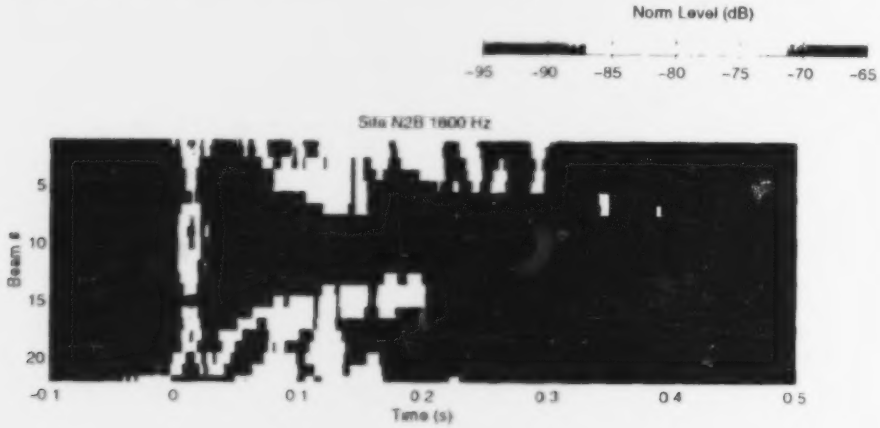

Figure 5. Measured beam time series at Site N2 at 1800 Hz: the quantity plotted is the ratio of received level and source level in dB. The water depth and source depth are 80 m and 56 m respectively. Time=0 is the pulse initiation, the pulse is observed on all beams on the direct blast due to clipping.

In addition to the vertical receive array, data were also received on a 96 element volumetric array, configured in 3 parallel planar, horizontally-oriented, star patterns of 32 elements each. The array was steered to the horizontal. Figure 6 shows the array response at 1800 Hz at Site N2 and at Site N1X. The data at Site N2 are relatively noisy and require further processing, but show some clutter events. At Site 1 there are several strong clutter events that may correlate with clutter events observed at 400 Hz. Future work will reprocess and geo-reference these data and determine if the buried river channels are responsible for the clutter features.

4. Summary

Local seabed reflection and scattering data were collected in the STRATAFORM area in support of GeoClutter objectives. These data will be processed to extract deterministic and stochastic geoacoustic data that will aid in modeling the long-range reverberation data. Samples of initial processed data were shown from Sites 2 and 1.

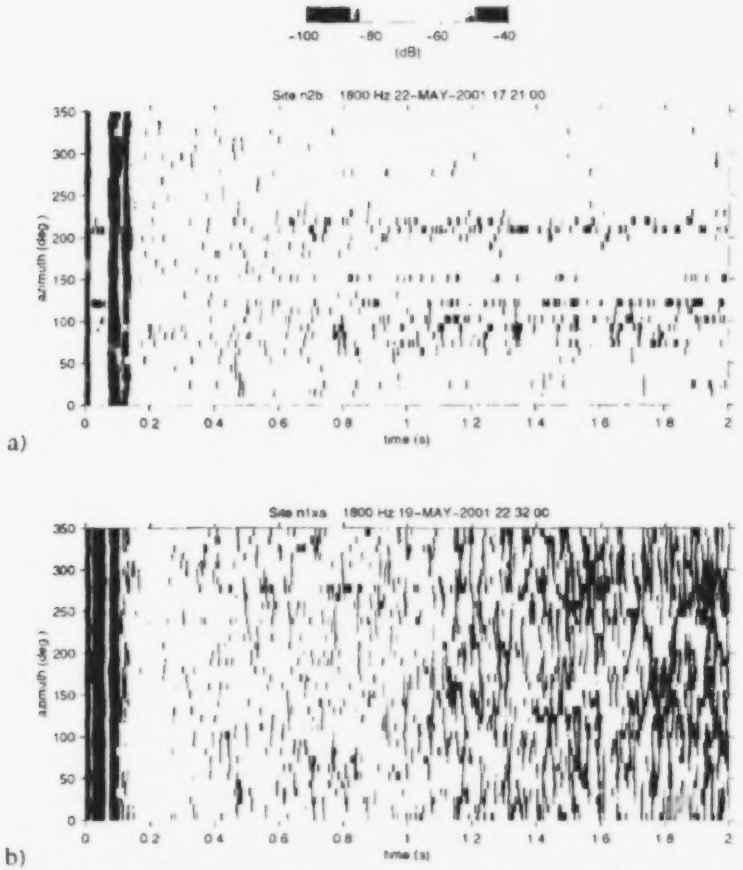

Figure 6 1800 Hz reverberation received on planar array at a) Site N2B and b) Site N1x.

5. References

Holland, C.W., "Regional extension of geoacoustic data", in Proceedings of the Fifth European Conference on Underwater Acoustics, ECUA 2000 Lyon, France, ed by P. Chevret and M E. Zakharia, 793-798, 2000.

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Holland, C.W . and J. Osler "High resolution geoacoustic inversion in shallow water: A joint time and frequency domain technique," *J. Acoust Soc. Am.*, 107, 1263-1279, 2000.

#517150 (3)

Measurements of time spread on the New Jersey Shelf using time-forward and time-reversed signals

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Mid-frequency shallow-water propagation measurements were made at three sites on the New Jersey Shelf during Boundary Characterization 2001 to extract measures of time spread and signal coherence, and to evaluate the spatial robustness of time reversal techniques. The experiments had the R/V *Alliance* periodically transmitting a 1-s, 1500-1700 Hz upswept LFM while it traversed an arc about the stationary R/V *Endeavor*, which captured these signals and transmitted back time-forward and a set of time-reversed versions of them, as well as transmitting its own version of the original signal. Initial analysis of normalized matched-filter data indicate that two-way signal spreads were small and that time reversal does well in reconstructing the original impulse response of the LFM. These time-reversed signals also exhibited a high degree of spatial robustness, with stored time-reversed signals statistically doing as well as "*in situ*" time-reversed signals.

Introduction

It is well known that geometric dispersion can cause appreciable time spreading of impulsive signals, even in the relatively simple case of a range-independent environment [1-2]. Understanding the role of the environment is essential to predicting dispersion and, hence, to the effective deployment and operation of sonar systems in shallow water (such as the choice of waveform or classifier). When it comes to predicting propagation, there are both deterministic and stochastic sources of errors. The deterministic errors originate primarily from a lack of sufficient environmental data (such as *in situ* sound speeds and geoacoustic data). The stochastic sources of error are many. Some, like range variations in the sound-speed structure and/or geoacoustic range dependence are really deterministic. As acquiring such environmental information is impractical, it is much easier to ascribe some portion of the observed fluctuations to this lack of perfect knowledge. In addition, there are actual stochastic processes, generated by internal wave fields, sea surface wave motion, and source/receiver depth variations caused by surface wave motion.

There are several approaches that have been developed for minimizing the effects of environmental mismatch. One promising area is the use of inverse methods for estimating some of the geophysical parameters from acoustic data. Another approach is aimed at developing *in situ* techniques that require minimal knowledge of the environment, such as phase-conjugation (acoustic time reversal) [3-5]. In this experiment, the primary goal was to investigate the spatial (and temporal) robustness of phase-conjugation (acoustic time-reversal) techniques for mitigating environment-induced signal degradation and distortion. The data collected will also be used to characterize time spreading and transmission loss.

P517150.PDF [Page: 4 of 6]

Experimental locations and procedures

The basic strategy is to place two platforms at a fixed separation, then have one periodically transmit a broadband signal, and the other capture these signals and transmit various time-reversed versions of them back to a receiver on the first platform. As these various versions correspond to different source-repeater-receiver paths, a comparison of their signal correlations provides a measure of the spatial robustness of phase conjugation in the given environment. (The more tranversely isotropic the environment, the more spatial robustness is expected.) Additionally, a standard (time-forward) echo repeat and a channel-characterization signal—the same as the original broadband signal—are broadcast from the second vessel as well. (The former provides a measure of how well time reversal is working, while the latter provides a measure of 1-way propagation characteristics.) The geometry chosen for Boundary 2001 had the R/V *Endeavor* as a stationary echo-repeater platform and the R/V *Alliance* as a mobile source-receiver platform (Fig. 1). (At Site S3 only, the SACLANTCEN VLA was deployed as well.)

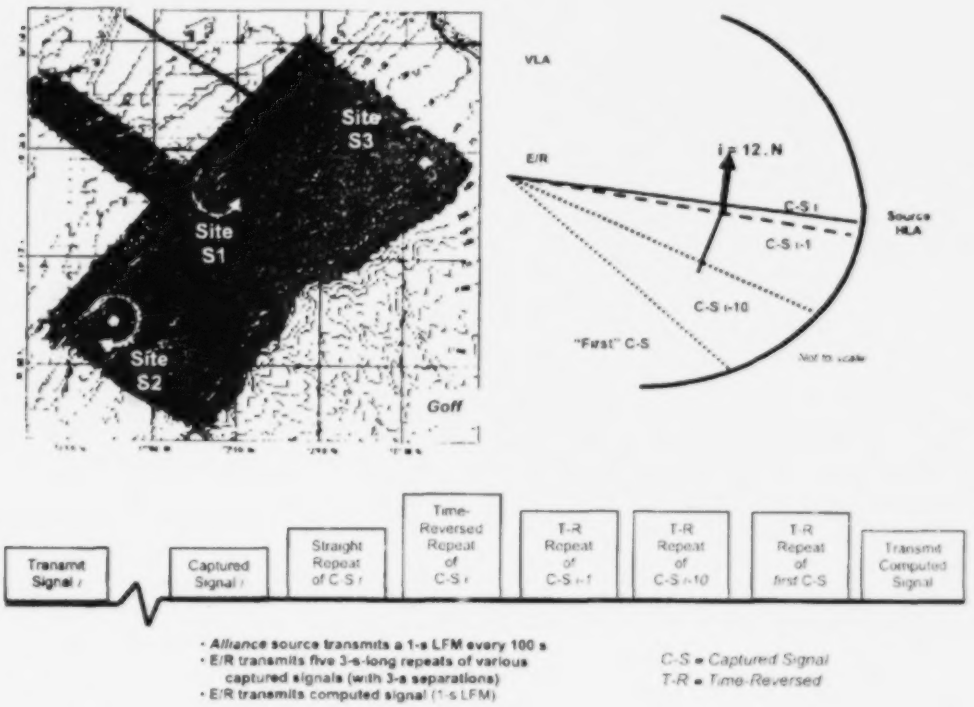

Figure 1 Measurement sites and geometry (top), and transmission strategy (bottom)

Experimental locations and procedures

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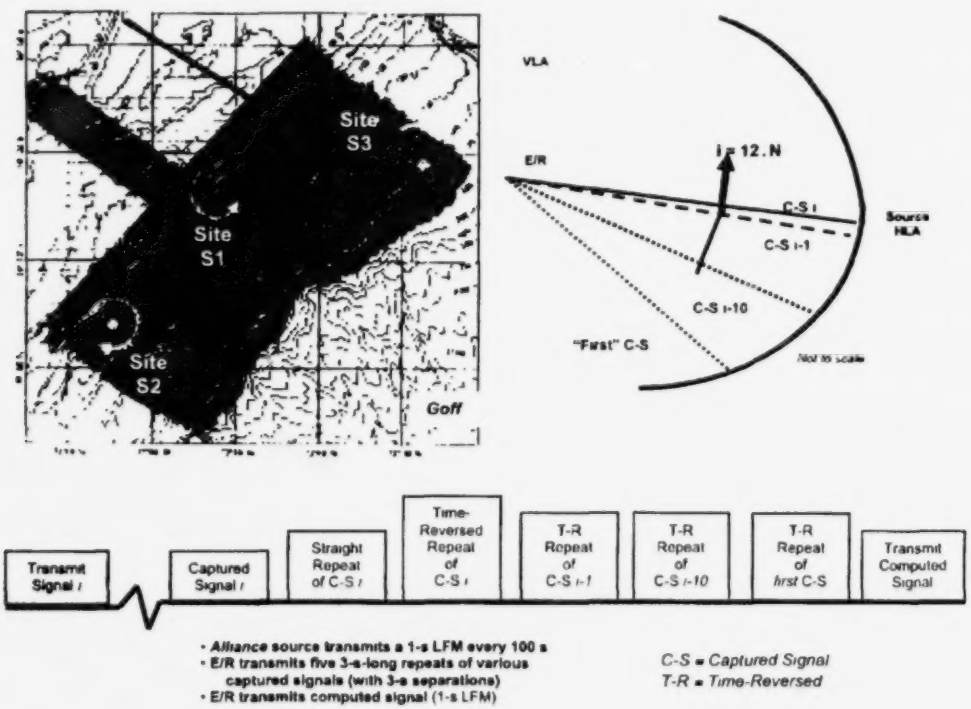

Figure 1 — Measurement sites and geometry (top), and transmission strategy (bottom)

Figure 2 presents typical unnormalized matched-filter output from the broadside beam of the R/V *Alliance* receive array, showing the initial transmission (and reverberation decay), and receipt of the corresponding sequence of the five echo-repeats from the R/V *Endeavor*. (The separation between the platforms was ~ 4.5 km.)

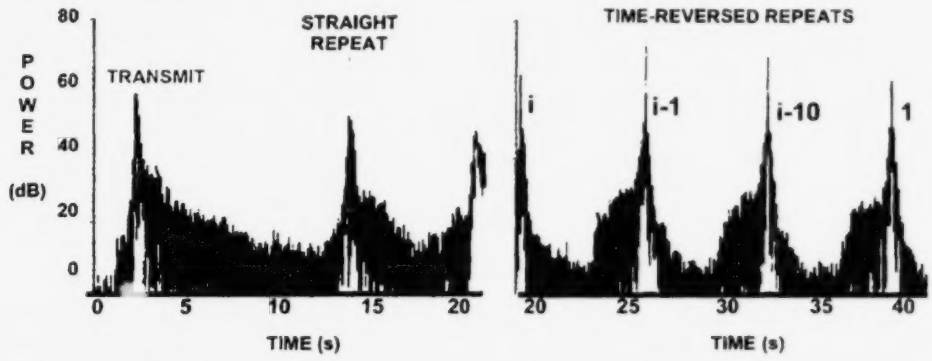

Figure 2 — Representative time-forward (left) and time-reversed (right) time series

Preliminary results

To extract useful measures of signal coherence and time spread, the matched-filter output are (energy-)normalized to remove nonstationary reverberation effects. The resulting time series can then be compared to the ideal impulse-response function of the 1-s LFM signal. Figure 3 shows such a time series for a representative sequence of time-forward and time-reversed signals from Site S1. By comparing their correlation with the theoretical (ideal) response, it is seen that relatively small spreads were seen. (Ping-to-ping fluctuations were also small.)

Time reversal generally yielded somewhat higher *peak* correlations and improved pulse compression over straight repeats, with the best performer typically being the $i\text{-}1^{st}$ time-reversed signal. Furthermore, time reversal appeared to be relatively spatially robust in these environments, with the $i\text{-}10^{th}$ time-reversed signal often performing as well as i^{th} time-reversed signal. However, the performance of the time-reversed retransmissions of the first captured signals (T-R 1) did not fare as well.

Plans

Immediate analysis plans include (1) quantifying one-way, two-way, and two-way time-reversed time spreads and signal coherence vs. environmental factors (such as sound-speed variations); and (2) computing/modeling transmission loss (when geophysical data are available).

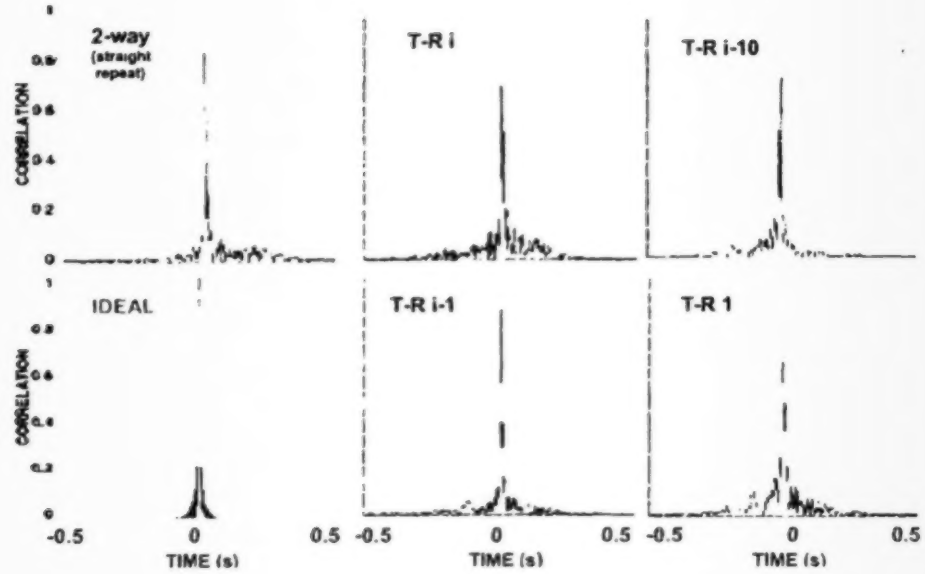

Figure 3— Representative time-forward and time-reversed normalized time spreads

Acknowledgements

This work was supported by the Office of Naval Research.

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#517151 (4)

Measurements of mid-frequency scattering strengths on the New Jersey Shelf

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Direct-path, monostatic scattering measurements were conducted at 18 sites across the New Jersey Shelf during Boundary Characterization 2001. Using combinations of short-duration cw and LFM signals, the goal was to determine both the mean (scattering strength) and statistical (probability density function) characteristics of the bottom-interaction zone at each site. Coupled with the supporting environmental measurement results, the 1-10 kHz acoustic data are being used to help sort out the relative contributions of different bottom-zone scattering mechanisms (water-sediment interface, sediment volume and, at low scattering angles, near-bottom fish) to the observed reverberation, as well as to invert for geophysical quantities such as bottom roughness spectral parameters. Initial bottom-zone scattering strength results show that many sandy sites exhibit a generally flat dependence on grazing angle (over 20-70 deg) and a moderate dependence (~5 dB) on frequency over 2.5-5 kHz, with some suggestion of fish scattering at 1-1.5 kHz.

Introduction

For a mid-frequency (MF; 1 to 10 kHz) active sonar, scattering from the ocean boundaries and biologics, coupled with propagation conditions, can severely limit the detectability of returns from features of interest. Furthermore, reverberation levels can vary dramatically, depending on the local geology, oceanography, and biology. Hence, making accurate predictions of active sonar performance will in turn depend on finding suitable models that accurately describe the scattering. The Naval Research Laboratory (NRL) has been developing physics-based models [1] of scattering strength, with an emphasis on generating formulas suitable for inclusion as submodels in both active performance/reverberation models and inverse algorithms (such as environmentally adaptive techniques).

To evaluate and determine the limitations of these models, NRL performed MF backscattering measurements at 18 sites on the New Jersey shelf. The goal was to determine both the mean (scattering strength) and statistical (probability density function) characteristics of the bottom-interaction zone at each site. This paper describes the initial bottom-zone (bottom + fish near the bottom) scattering strength measurements from 8 of these sites.

Test operations and data processing

Direct-path, monostatic scattering measurements were conducted from the R/V *Endeavor* at 18 sites (Table 1) across the New Jersey Shelf (Fig. 1), using a 16-element vertical line array (VLA) receiver cut for 5000 Hz, and single source (F80). (Halfway through the test, the VLA developed a leak, and a single hydrophone was used in its place.) Measurements were made using combinations of short-duration cw and LFM signals. For the 8 VLA sites, the sonar equation was used to derive scattering strengths as a function of beam, frequency, and grazing angle.

Site	VLA or Phone	Date (JD) Time (Z)	Latitude (deg N) Start Stop	Longitude (deg W) Start Stop	Water Depth (m)	Water Sound Speed at the Interface (m/s)
K7	VLA	132 0835-0920	39 15.64 39 15.70	72 54 63 72 54 08	76	1494
K8	VLA	132 1039-1113	39 13.18 39 13 28	73 00.42 73 00 27	76	1494
K2	VLA	132 1346-1444	39 15.06 39 15 05	72 43.07 72 43.31	120	1494
K9	VLA	133 0319-0354	39 07 06 39 06.83	73 04.14 73 03.81	75	1473
K11	VLA	133 0556-0633	39 03.15 39 02 53	73 07 01 73 06.70	71	1473
K10 S2	VLA	133 1430-1626	39 04 29	73 04.49	84	1474
K12	VLA	134 0819-0854	39 04 04 39 03.13	72 58.36 72 58 46	85	1492
K16	VLA	134 1334-1405	39 24.34 39 23 59	72 33 91 72 34.23	110	1497
K1 S1	Phone	135 1721- 136 0114	39 16 12	72 51.68	80	1489
K17	Phone	136 1152-1252	39 25.50 39 24 29	72 41.00 72 43 32	90	1494
K18	Phone	136 1354-1457	39 27.80 39 27.17	72 42 78 72 44 24	78	1478
K15 S4	Phone	136 1848-2035	39 16.41 39 15 65	72 33.16 72 33 28	140	1502
K5	Phone	136 2153-2236	39 16.32 39 15.65	72 28.11 72 28 58	148	1502
K6 S3	Phone	136 1802- 137 0011	39 19.26	72 27 67	140	1500
K4	Phone	139 0009-0103	39 13.30 39 13 41	72 33.40 72 33.68	140	1501
K3	Phone	139 0201-0229	39 13.59 39 13.54	72 39.61 72 39 86	130	1498
K14	Phone	139 0338-0410	39 09.69 39 09.48	72 42.39 72 42.50	140- 180	1496- 1494
K19	Phone	139 1627-1632	39 02.03 39 02.00	73 02.28 73 02.53	80	(no data)

Table 1 R/V Endeavor Boundary 2001 scattering measurements

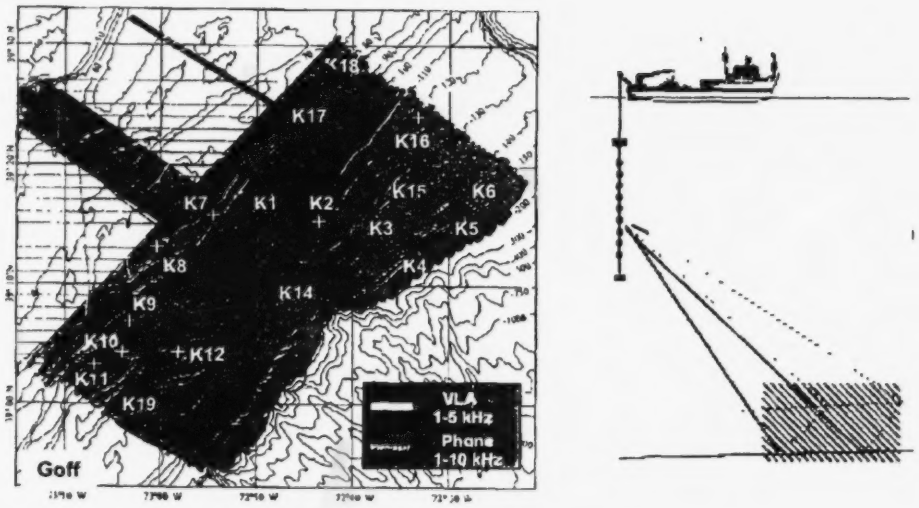


Figure 1 R/V Endeavor Boundary 2001 scattering sites and geometry

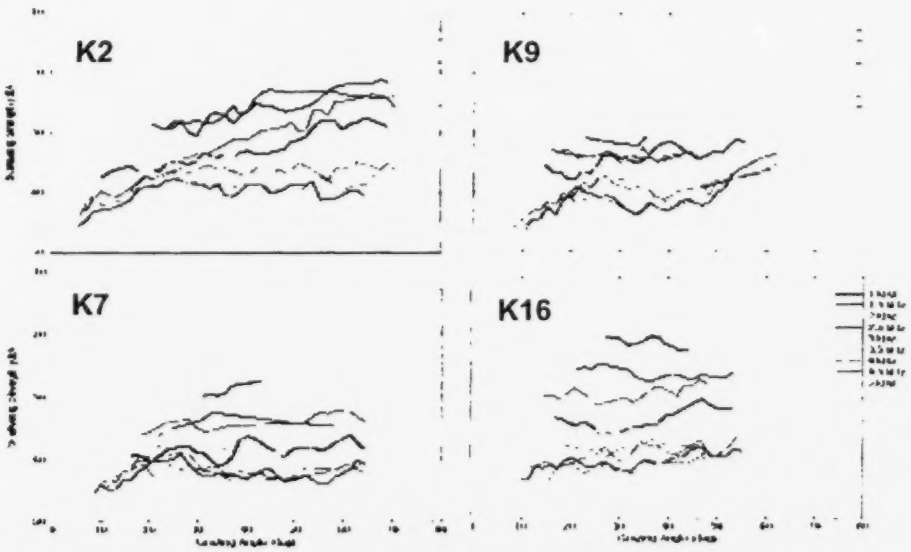
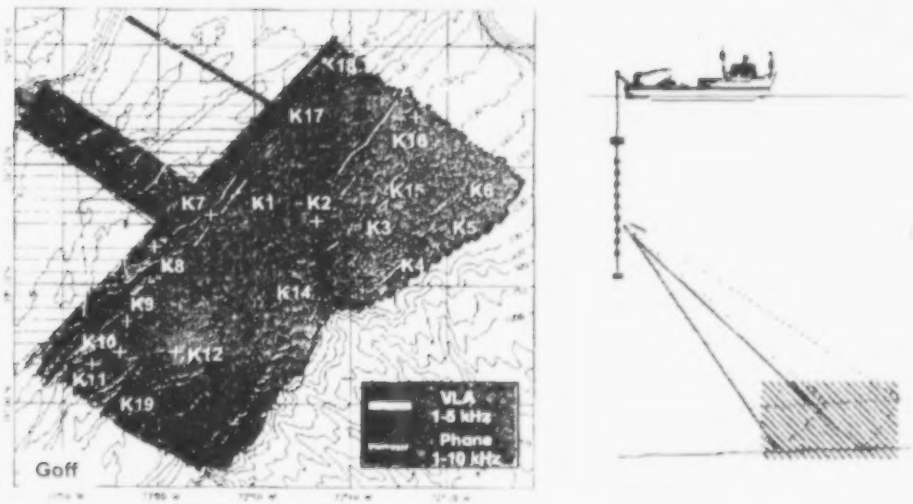


Figure 2 Scattering strength vs grazing angle and frequency for 4 sites



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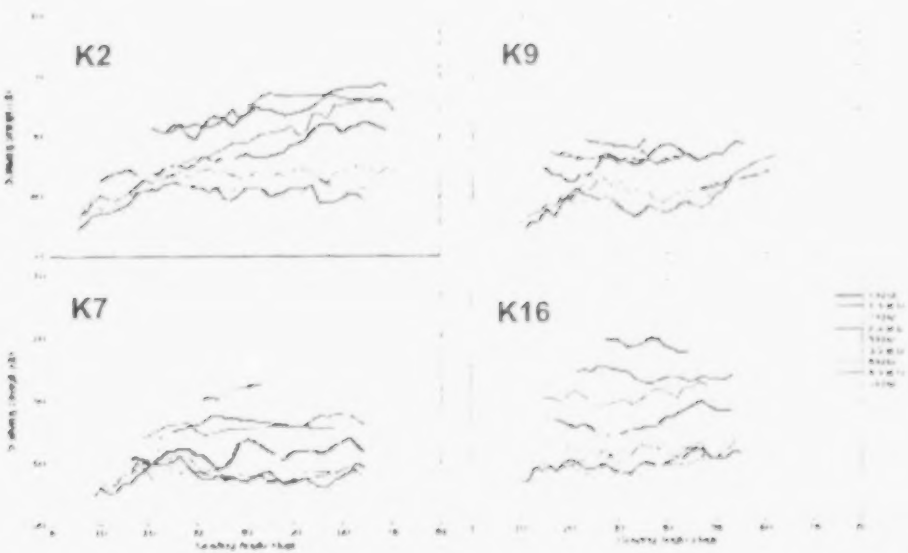

Figure 2 Scattering strength vs. grazing angle and frequency for 4 sites

Preliminary results

An immediate issue is calibration: concurrent measurements using both the F80 and G81 sources at the 3 moored sites (with the same VLA) showed the F80 scattering strengths to be up to ~8 dB below those using the G81. However, calibration-issues aside, site-to-site comparisons of the *relative* dependence of backscattering strength on grazing angle and frequency are still possible. Figure 2 illustrates that significant site-to-site differences were sometimes seen in the backscattered levels, predominantly at 1-2 kHz. Across the eight VLA sites, some general trends were observed:

Grazing-Angle Dependence: Most sites exhibited a generally flat dependence on grazing angle (over 20-70 deg), with some suggestion of a compressional critical angle around 20 deg.

Frequency Dependence: A peak at 1 kHz, with generally decreasing scattering strengths with increasing frequency (to 5 kHz). There was a strong site dependence in the 1-2 kHz band (perhaps suggestive of fish scattering [2]), with a moderate dependence on frequency over 2.5-5 kHz, especially below 20 deg.

Plans

- To resolve the calibration issue, we will calibrate both sources, and examine the desensitized phone data to try to estimate the *in situ* source levels directly.
- Refine the processing and analysis, such as correcting for multipath effects and nonstationary reverberation-decay effects.
- Model these and the Holland- and Hines-derived boundary scattering strengths once estimates of geophysical (and oceanographic) parameters are available.
- Extract/model scattering probability density functions from LFM signals.

Acknowledgements

This work was supported by the Office of Naval Research.

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Chirp sonar inversion results from Boundary Characterization 2001 and Shallow Water Acoustic Technology experiments

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Sub-bottom surveys have been conducted during recent Boundary Characterization and Shallow Water Acoustic Technology (SWAT) experiments to invert for bottom geoacoustic properties on the New Jersey Shelf. Sediment properties such as density, porosity and sound-speed profiles are inverted by using reflection amplitude and phase data obtained from a hull-mounted 2-10 KHz chirp sonar and a deep-towed 2-12 kHz chirp sonar. The attenuation coefficient is estimated using the frequency-shift method that seems to be relatively insensitive to reflection and transmission effects. Using a USGS vibracorer, several sediment cores (up to 4.5 m long) along the chirp survey tracks were also collected during the SWAT experiment. Both systems provided high-quality reflection data and preliminary analyses indicate that inversion results are in agreement with those of sediment core measurements.

Introduction

Using calibrated echo-sounding sonars, acoustic reflection amplitude and phase data can be inverted for bottom geoacoustic properties by assuming homogeneous layering within the seabed.[1,2] During the recent Boundary Characterization and Shallow Water Acoustic Technology (SWAT) experiments, high-quality chirp sonar data have been collected to characterize the bottom at Naval Research Laboratory scattering sites and along the SWAT acoustic propagation tracks at the New Jersey Shelf. Several co-located sediment cores were also collected to validate the chirp sonar inversion results. In this paper, an overview of the chirp data and SWAT core data analysis is given. Preliminary inversion results and core measurements at several sites are also presented. The results should be treated with a caveat since a more complete and through analysis is underway.

Overview of chirp sonar and vibracore measurements

Chirp sonar data were collected by a hull-mounted sonar on R/V *Endeavor* at the acoustic propagation and scattering sites within the STRATAFORM experimental area (see Fig. 1). Sediment cores were collected at 14 sites using a Vibrocore system from USGS which was limited to 100 m or shallower water depths. Chirp sonar data co-located with the core sites were also collected by using a deep-towed system. Under the SWAT project, a comparison of seabed properties obtained by core measurements and chirp sonar inversions has been started at H5 and H5A core sites. Also, chirp sonar inversion results along the acoustic propagation tracks S1 and S2 are being used in the propagation models to study shelf-edge acoustic propagation. During the Boundary Characterization experiment, a hull-mounted sonar system was used at 35% power for the first three runs that limited penetration into the bottom. However, Run 4 and Run 5 were performed with 70% power and coherent acoustic returns were observed from 30 m below seafloor. Inversions of chirp data were attempted at K2 and K16 scattering sites. Figure 2 shows a subbottom profile along ~80 m bathymetry contour which was obtained at the end of Run 5 while the R/V *Endeavor* is heading back to port at 10 knot cruising speed. The spikes above the seafloor are schools of fish near the bottom. Two inserts are also provided in Fig. 2 to describe the shapes and dimensions of the fish schools. Figure 3 shows the subbottom profiles obtained during Run 1 and Run 4 between the acoustic scattering sites. High-quality subbottom images at

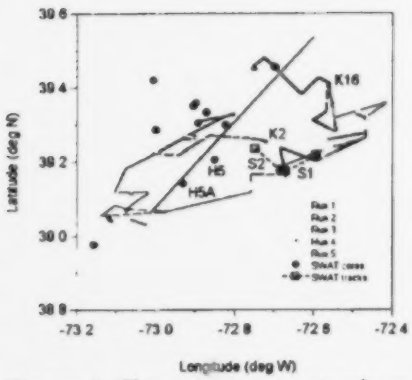

Figure 1 Chirp sonar survey tracks and propagation, scattering, and core sites

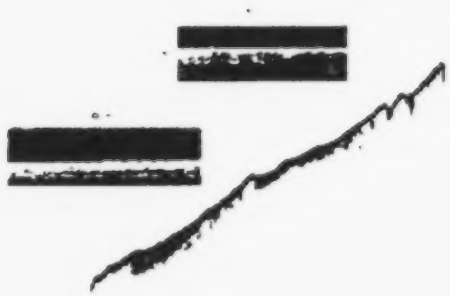

Figure 2. Chirp subbottom profile at 80 m contour and fish schools near the bottom

Figure 3. Chirp subbottom profiles between the scattering sites.

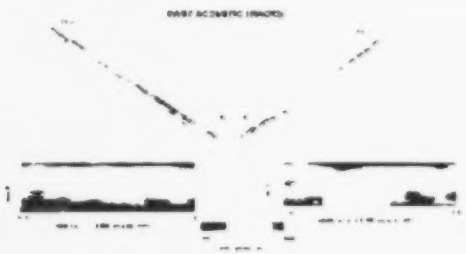

Figure 4. Subbottom profiles and inverted sound-speed structure at the propagation site

these scales should help to describe the geology of the area as well as to identify potential geoclutter sites (buried river channels, sediment boundaries, erosional scours, etc.).

Chirp sonar inversion results

In this section, preliminary results of chirp sonar inversion at the acoustic propagation/scattering sites (S1, S2, K2, and K16) and core sites (H5 and H5A) are presented. Figure 4 shows the subbottom profiles along the SWAT acoustic propagation tracks and 2-D images of sound speed distribution obtained from the inverted sound-speed profiles with 700 m separation. In general, the ranges of inverted sound speeds correspond to those of silty sand to sand. A detailed analysis

providing a higher horizontal sampling is underway. In Fig. 5, inverted sound-speed profiles at the core sites and scattering sites are given. The inverted sound-speed profiles are compared with

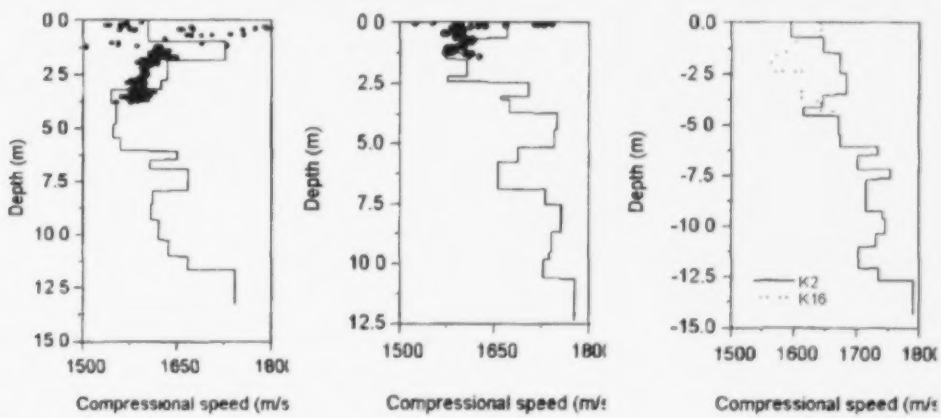

Figure 5. Inverted sound speed profiles at sites H5 (left), H5A (middle), and K2 and K16 (right). Comparisons with core measurements at sites H5 and H5A (provided by W. B Sawyer[3]) are also shown.

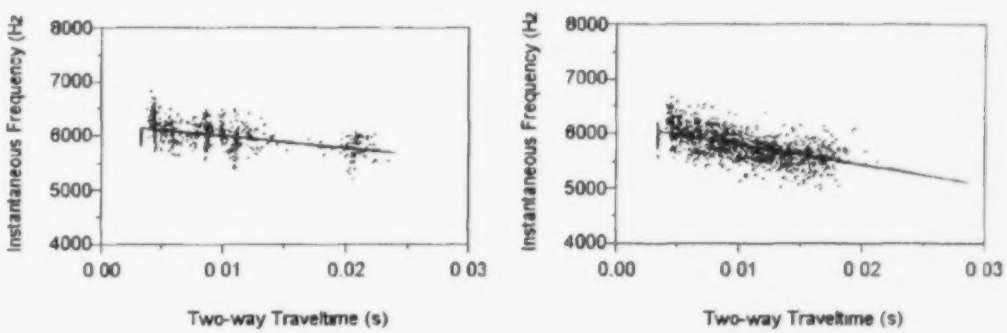

Figure 6. Instantaneous frequencies measured at sites K2 (right) and K16 (left) for 200 pings. Center frequency shifts per distance were calculated by a least-squares line fit

those of core measurements are shown in Figs. 5a and 5b High-resolution core measurements of compressional speed were done using a core logger [3] While the inversion results compare well with the core measurements, core data depicts very high and scattered values near the water/sediment interface. At the moment, the rationale for these high compressional speed values is not known. It might be due to sediments with large shells being disturbed near the interface. Also, a large number of cores were collected in aluminum core liners that might introduce additional complexity in the measurements. A complete geotechnical analysis of core measurements will be performed in the near future that might help to resolve this issue. Figure

5c shows the compressional speed profiles obtained at the scattering sites K2 and K16. At the K16 site, acoustic return is limited to a few meters due to more homogenized and coarser sediment layer being risen from 15-20 m depths to 1-2 m depths. More elaborate inversions will be performed at other scattering sites with ~20 m horizontal resolutions. Figure 6 shows the measured instantaneous frequencies for 200 pings at each scattering sites The center frequency shift (calculated from the linear fit to the data) should be a good measure of attenuation estimations for both sites. The calculated values are 14 Hz/m and 22 Hz/m for the sites K2 and K16, respectively. Pulse propagation/reflection simulations within the same frequency band produce similar center frequency shift for silty sediments at the K2 site and sandy/silty sediments at the K16 site.

Summary

An overview of the analysis of the chirp sonar data collected during the recent Boundary Characterization and SWAT experiments are presented Both data sets are of high quality and will be further analyzed to support the bottom characterization efforts of Boundary Characterization and SWAT research groups. As a proof-of-concept and consistency check, further comparisons of the inversion results with the sediment core measurements will be also performed in the near future.

Acknowledgement

This work is supported by ONR Chirp sonar and core data collection efforts of both SWAT and Boundary Characterization research groups are greatly appreciated.

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#517153 (6)

Fish scattering during Boundary Characterization 2001

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During Boundary Characterization 2001 a high frequency echosounder was used to derive general fish distributions and spatial statistics while a mid frequency (2 to 10 kHz) omnidirectional sonar was used to determine their scattering character. Most notable were schools of fish occurring around the 80 m contour. These fish were in tight schools within 5 m of the bottom during mid day and dispersed into loose schools 10 to 20 m off bottom at night. High frequency layer scattering strengths within the schools generally ranged from -40 to -30 dB with levels as high as -28 dB occurring in several scattering "hot spots". These hot spots were investigated with casts of the mid frequency sonar. Generally flat spectra with a gradual increases of several dB from 4 to 2 kHz suggest that the fish in the hot spots were an intermediate sized fish with a swimbladder (likely 20 cm scup). Extrapolation to lower frequencies using a standard swimbladder model gives a peak layer scattering strength for the hot spots as high as -15 dB at 1 kHz. Navigation data indicates that the hot spots were on the order of several hundred meters across. [Work supported by ONR.]

Introduction

The greatest source of volume scattering below 5 kHz is from the swimbladder resonance of fish [1]. This biological volume scatter can cause clutter or false targets on search sonars or can confound measurements of shallow grazing angle scattering from the sea surface or sea floor [2]. At the Boundary Characterization 2001 (BC2001) site, a wide variety of fish species could potentially occur. Which species would actually be present is determined by species specific preferences for oceanographic conditions. In addition, these fish could, depending on the time of day and species, potentially occur in schools, shoals, or layers, on or near the sea floor (demersal), in midwater, or near the sea surface (pelagic).

This paper summarizes measurements of fish density and school characteristics made by the Naval Research Laboratory (NRL) aboard the R/V Endeavor during BC2001, using a 38 kHz Simrad EK500 fisheries echosounder and NRL's Mid-Frequency Fisheries Sonar (MFFS). The echosounder was used to provide a rapid survey of the site giving fish occurrence, density, and school statistics. MFFS was used to provide a 2-10 kHz spectral signature of select schools. Measurement of the scattering at 2-10 kHz combined with species size information available from the National Marine Fisheries Service (NMFS), allows extrapolation of volume scatter to frequencies below 2 kHz using NRL models of swimbladder resonance [3]. Results for demersal fish are presented first since they were by far in greater abundance than the pelagic fish.

Demersal Fish

Echogram data were obtained over a total track length of 1,020 km. The echogram data were processed using an image processing algorithm [4, 5], set to enumerate and measure fish school like targets, defined as those with a 38 kHz volume scattering (SV_{38}) threshold exceeding -60 dB. This analysis included a visual examination of the echogram data to ensure only the inclusion of fish-like targets and the elimination of plankton and surface bubbles (originating during ship turns/maneuvering or rough weather). In this analysis 1,459 demersal fish schools were identified (Fig. 1).

The demersal schools were most readily observed at night as loose aggregations of fish within 10 to 20 m of the bottom. During the day the fish aggregated into dense schools either 5 to 10 m above the bottom, or in some cases were so close to the bottom as to be barely detectable with the echosounder's 1 ms length pulse. Figure 1 shows that these

schools occurred primarily over bottom depths of 75 to 85 m. There was some evidence from repeated surveys of the same region, that over 5 days, the fish appeared to migrate 5 km upslope from the vicinity of the 100 m contour to about the 80 m contour. This is indicated in Figure 1 by the letters A (May 11) and B (May 16).

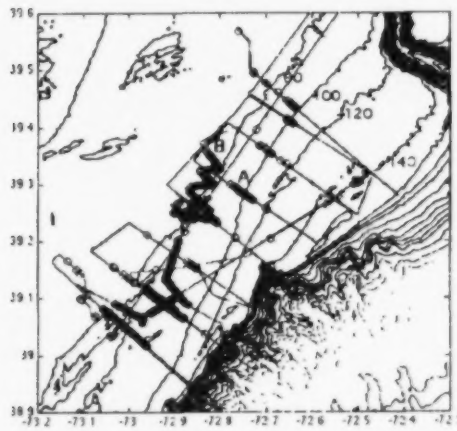

Fig. 1 Distribution of demersal fish during BC2001, each small circle represents the observation of a demersal fish school (red circles) along the survey trackline (green). Bathymetric data were supplied by Nick Chotiros.

To better examine the fish concentrated along the 80 m contour a small-scale survey was conducted using the MFFS and echosounder in a zig-zag search pattern (track SW of B, Fig. 1). Unfortunately, because of choppy sea conditions and a low S/N ratio the MFFS did not detect the demersal schools during this survey. However, echosounder data were obtained giving peak and average within school layer strengths of -30 dB and -40 dB, which would be equivalent to fish densities of 10 and 1 fish/m^3, respectively (assuming a 38 kHz target strength, TS_{38}=-40 dB).

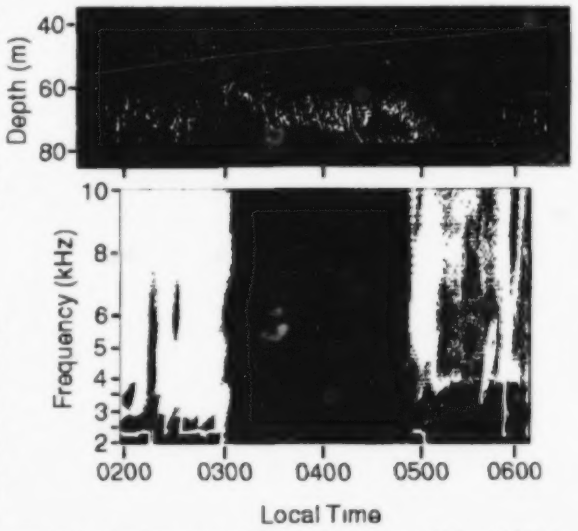

Fig. 2 Upper panel 38 kHz echogram (SV -40 to -80 dB), and lower panel 2 to 10 kHz spectral record (Layer Strength -20 to -60 dB). At about 0300 the density of fish increased greatly and remained high until dawn, at 0500. Echoes at 47 and 52 m in the upper panel are from the MFFS source receiver package. The dark blue portion of the spectral record is where the S/N ratio was too low to allow a backscatter measurement.

During the night of May 18-19, the MFFS omnidirectional source and receiver were lowered close to a large number schools. The fish were at 60 to 80 m, near the 80 m contour about 2 km to the southwest of site K1/S1. With the ship drifting over the fish, the source/receiver was lowered to 47 m depth, a position about 10 to 15 m above the fish. The fish were ensonified at frequencies of 2-10 kHz from 0200 to 0600 h. Data obtained with the narrow 7° beam of the echosounder, show both the MFFS source receiver package and the fish schools, and allows an excellent spatial correspondence between the source/receiver and the target schools (Fig. 2).

Although a generally flat spectrum was obtained from the most intense portion of the 'cast' data (Fig. 2), there is a slight rise toward the lowest frequencies that suggests the data are

from fish with a swimbladder resonant below 2 kHz (Fig. 3). The data cannot be from the geometric scattering of non-swimbladder bearing fish, such as dogfish shark or butterfish, which would show a drop of 12 dB per octave (Rayleigh scattering) below about 5 kHz.

Three species of demersal fish that have swimbladders, silver hake, red hake, and scup, are all candidate scatterers. All three were caught in bottom trawls taken in the BC2001 area one month prior to the experiment [6]. Three arguments further refine the identity of these scatterers: 1) their physical oceanographic preferences; 2) their expected resonance based on the size data from the trawls as modeled and matched to the MF data, and 3) their observed high frequency TS from the echosounder.

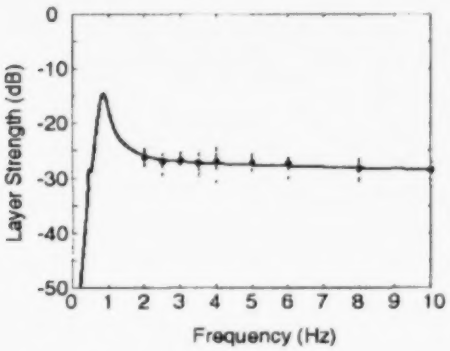

Fig. 3 Average layer scattering strength (red: average and actual values) and model fit for scup (blue)

CTD and XBT casts taken during BC2001 show that the demersal fish schools near S1/K1 were in a 10-20 m thick layer of water near 9-10 °C. Of the three candidate species, only the scup show a strong affinity in the spring for 9-10 °C water at bottom depths of 70 to 80 m [7,8,9]. In the spring, red hake tend to occur at shallower depths (50-75 m) at cooler temperatures (6-7 °C), and silver hake tend to occur in deeper water (100-200 m), also at cooler temperatures (7-9 C). During the cast experiment, estimates were made of the single fish TS_{is} distribution in and around the edges of the schools using the echosounder. The TS_{is} distribution extended from -50 to -35 dB with a peak at -40 dB. Empirical relationships of fish length to target strength [10], suggest that the observed TS_{is}'s were from 15-25 cm length fish, providing further evidence that the fish were likely scup. The column strength data (Fig. 3), suggests that scup density can be as high as 16 fish/m^2. Finally, in Fig. 3 a comparison is shown between the MFFS cast data and a swimbladder model (blue curve) based on the size distribution of scup obtained from the NMFS trawls. The curve shows an excellent fit to the data and suggests a low frequency resonance is likely to occur at about 900 Hz with a resulting layer strength as high as -15 dB.

Because the demersal fish observed during this experiment appear to have moved during the course of the experiment, our best assessment of volume scattering and the density of demersal fish at the NRL bottom scattering sites is from data collected using the echosounder simultaneously with, or close in time to, the bottom scatter measurements. Only a rough qualitative assessment of the scattering at these sites is available at this time. The highest fish density was observed at site S1/K1, which had a continuous layer of demersal fish (previous section) all within 1 m of the bottom. Site K12 had a moderate number of fish in a layer 2-8 m off bottom, while sites K7 and K8 had lesser numbers of fish 1-5 m off bottom. Four sites, K10/S2, K16, K18, and K19 had only an occasional fish observed. At six sites, S3, K3, K4, K11, K14 and K17 no fish were observed.

Pelagic fish

Schools were considered pelagic fish based on their close association to the sea surface and spherical section shape. However, pelagic schools were under represented in this study because they occur close to the sea surface, a region under sampled by the echosounder. The upper 8 m of the water column was not sampled because of the hull mounted echosounders

depth (6 m) and the slow towing speed of the MFFS (4 kts) precluded it from being used during the site-wide survey.

Only 16 pelagic schools were detected and and quantitatively measured using the same analysis as for the demersal fish. Based on the total water volume ensonified during the survey, the overall density of the pelagic schools was about 5.2 schools/km^2. Most of these were detected in the daytime near the northern corner of the site (near K18), generally over depths of 70 to 100 m. Confining the density estimate to just this region gives about 20 pelagic schools/km^2. Extrapolating school section size to volume and summing TS_{is} gives potential TS of the schools ranging from -32 to +23 dB with a mean of 0 dB. The fish present in the pelagic schools may have been one of several species of fish which are expected on the outer continental shelf in May [11]. Possible candidates are Atlantic mackerel and butterfish (no SB), alewife, and/or Atlantic herring. The presence of non-swimbladder bearing species could result in almost no acoustic signature below about 5 kHz.

On May 14 at 2100 both the MFFS and echosounder detected a large shoal of pelagic fish, approximately 3.2 km in extent and at 10 to 30 m depth at 39°5.9' N, 72°55.8' W. The spectrum for this shoal was flat at 5 to 4.5 kHz and dropped by about 7 dB to 3.5 kHz and another 5 dB to 2 kHz. Echosounder data and swimbladder modeling both suggest that the fish were probably small, about 2-4 cm. About 1000 estimates of TS_{is} were tightly grouped around a mean of -58 dB, which is roughly equivalent to a fish of about 2 cm length. The location of this shoal, over bottom depths of 85 to 88 m, just inside the shelf break would suggest either larval fish of any number of fish species common to the shelf, or a mesopelagic fish associated with the shelf slope break, such as the pearlside, *Maurolicus muelleri*. Fish density, estimated from the echosounder SV data, show peak densities of about 2.5 ind/m^3, with a mean density near 0.06 ind/m^3. Considering the denser portion of the shoal was about 10 m thick, the average areal density of the shoal was about 1 ind/m^2

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Some shallow water reverberation highlights and bottom parameter extractions in the 325–825 Hz region from the 2001 Boundary Characterization experiment

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Abstract Together with SACLANTCEN, the authors recently participated in a sea trial to measure shallow water bottom reverberation near the STRATAFORM off New Jersey and on the Scotian Shelf Sources were monostatic SUS charges and coherent pulses The receivers were horizontal arrays Data were analyzed in bands from 80-4000 Hz Highlights of the reverberant returns are discussed The STRATAFORM is known to have benign surface morphology but contains many buried river channels One author was also involved in the 2001 Geoclutter experiment conducted in STRATAFORM using coherent bistatic sources near 400 Hz Differences in reverberation characteristics between SUS and Geoclutter results are discussed Another objective of this reverberation experiment was to quickly invert for scattering and geo-acoustic parameters A simulated annealing (SA) algorithm was used together with the Generic Sonar Model After automatically adjusting bottom loss and scattering strength, good agreement is achieved between the diffuse reverberation data and model predictions in relatively flat areas Model/data differences are generally correlated with bottom scattering features Since reverberation typically lasted 20 - 40 s or more, extracted parameters apply over wide areas Local bottom loss and backscattering measurements were made by Holland in these areas A comparison with preliminary results from Holland is given (Work Supported by ONR Code 32, Grant N00014-97-1-1034)

I. Introduction

The long-range reverberation measurements and analysis performed during the Boundary 2000 [1] and Boundary 2001 experiments were an extension of the work done from 1996 through 1998 in the NATO MILOC Rapid Environmental Assessment (REA) exercises, Rapid Response One purpose of the REA was to use previously developed reverberation research tools to develop techniques needed to provide products in support of ASW operations The reverberationanalysis in the REA exercises contains no direct measurements of the scattering. One main purpose of the current Joint Research Project (JRP) among SACLANTCEN, the US and Canada, is to validate the REA reverberation parameter extraction techniques by comparing these inversion techniques with more direct measurements of the bottom loss and scattering Also, the manual inversion procedure used in the REA exercises was quite labor-intensive and somewhat subjective, so an automated procedure for the parameter extraction was developed The sites chosen for the JRP are generally much flatter and more uniform than the sites for the NATO MILOC experiments This type of site selection is driven by a range independent limitation in reverberation models currently being used This paper briefly summarizes some reverberation results from a shallow water site called S1' on the STRATAFORM off New Jersey (Fig 1) and from a site on the Scotian Shelf More details of the methodology used here can be found in [1]

II. Long range reverberation measurements

A Overview

The reverberation measurements were carried out in conjunction with ambient noise measurements, as in previous REA and MILOC trials [2] The primary items needed for reverberation measurements were SUS charges deployed from R/V *Alliance*, and two horizontal towed line arrays. the 254 m three-aperture Prakla low-frequency array, and the 5 58 m single-aperture mid-frequency array Additional reverberation measurements were made using a towed broadband source, and the mid-frequency array as a receiver Extensive oceanographic and transmission loss measurements were also made as part of the sea trial Multiple tow directions are necessary to resolve the left-right ambiguity of the line array A procedure, based on a polygon track, was developed by Wagstaff for ambient noise [3] and adapted by Preston *et al* [4] for reverberation measurements. To improve the stacking procedure for reverberation, the polygon was replaced by a five-legged "petal" pattern in the Rapid Response exercises [2], in which the ship track on all five legs passes close to a common center point. Two arrays were deployed and towed at a speed of 4 to 5 kn On each leg, the arrays were allowed to stabilize (about 20 min), after which 10 to 20 min of ambient noise were recorded For

reverberation measurements, two or three SUS charges (of 0 818 kg, detonated at a depths of 91 or 18 m) were dropped near the center of the pattern, at 5 minute intervals. The length of time for the experiment is about 8 hours, including at about 30 minutes time required on the turns, as the average turning angle is 216° Further details of receiving arrays, data acquisition, processing and displays are in [1 and 2] The primary modelling program used is the Generic Sonar Model (GSM) [5] developed at the US Naval Underwater Warfare Centre We have had considerable success in using it to model reverberation It is a comprehensive eigen-ray-based sonar model which users array beam patterns and computes surface, bottom and volume reverberation and fathometer returns For calculating bottom loss curves in the automated inversion procedure, the normal mode code ORCA [6,7] was used also.

B Long Range Reverberation from STRATAFORM and the Scotian Shelf

This section describes a sample of the reverberation and ambient noise measurements made off New Jersey in the STRATAFORM on 15 May, 2001 (near N 39° 15.5' and E 72° 43') at a site called S1' and on the Scotian Shelf on 29 May, 2001 at a site called C4 (near N 44° 10' and E 61° 10') At the STRATAFORM site. the water depth was about 118 m R/V *Alliance* towed the Prakla low-frequency array (used for frequencies up to 1500 Hz) and the Mid-frequency array (used for frequencies up to 4 kHz) The "petal" pattern ship track was used, with SUS charges dropped at depths of 91 m while the ship was on 5 different headings Data from the Prakla array were recorded for 90 s. The sound speed was near 1502 m/s at the surface, with a very weak sound channel axis and a sound speed minimum of ~1496 m/s at a depth of ~ 90 m at this site The Prakla array was deployed to a nominal depth of 25 m Winds were fairly light. the bridge logs showed a Beaufort wind force ~3 At lower frequencies directional background noise was often present but ship traffic seemed to be moderate On the Scotian Shelf water depth was about 78 m and wind speeds very low (~5 knots) The sound speed near the surface was ~1478 m/s, the sound speed profile was downward refracting with a thermocline from 10-18 m and speed at the bottom of ~1459 m/s At this site 18 m SUS were used with the same basic petal pattern to collect reverberationdata Intermittent airgun activity was present at this site Other shipping was light

Fig 1 shows a stacked polar plot of the reverberation observed at site S1' at 350 Hz, as received on the Prakla array and overlaid on a bathymetry chart For these polar plots, the array beam angles are mapped into azimuth, and time is mapped into range (using an averaged 1503 m/s propagation speed) The black arrows show the five array headings, with the base of the arrows being the mid-points of the array at the time of the shot. Also shown in Fig 2 (courtesy of Goff) are buried river channels (black dendritic lines), sub-bottom horizons (red) and small topographic features (blue)[8] There is high reverberation (shown in red) at short ranges, decaying into the background (dark-blue and gray) at long ranges/times. Normally on a single shot there is left-right ambiguity and the acoustic features show up twice The stacking is a dB averaging over the 5 directions that eliminates most of the ambiguity [4]. Radial lines of high intensity are ambient noise from shipping and should be ignored for purposes here Strong anisotropic scattering is usually associated with bathymetric features Strong scattering can be clearly seen from the large orange colored protrusion NE of the center point which surrounds one of the R reflectors (red lines) noted by Goff [8]. To the NW of the R reflector is new sand and to the SE is stiff clay. More surprising are the strong returns from over the shelf break to the southeast near the 300 m contours Note that for this figure the bathymetry overlay includes surficial and sub surface scattering features mapped by Goff [8] The bathymetry structure was mapped to resolutions of about 30 m over the STRATAFORM.

Fig. 2 shows a stacked polar plot of the reverberation observed at site C4 on the Scotian Shelf at 630 Hz, as received on the Prakla array and overlaid on a bathymetry chart There again is anisotropy in the diffuse reverberation and a bit more clutter in the reverberation background than was seen on the STRATAFORM Airgun noise in the southwest quadrant contaminatesthe background ambient In the northeast quadrant a thin line marks the position of a pipeline running from 44° 20'N to the SE There appears to be a return that 'stacks' as one can see near the line center. Surprisingly, few of the strong bathymetric features to the west appear in the reverberation displays

III. Automated parameter extraction

In any attempt to model reverberation and pulse transmission it is important to have a good model of the seafloor One way to do this is to construct such a model by inverting for bottom parameters using reverberation time series A manual inversion procedure was used in the recent REA sea trials, e g [2] That procedure uses measured reverberation data and the Generic Sonar Model (GSM) [5] to perform a forward-

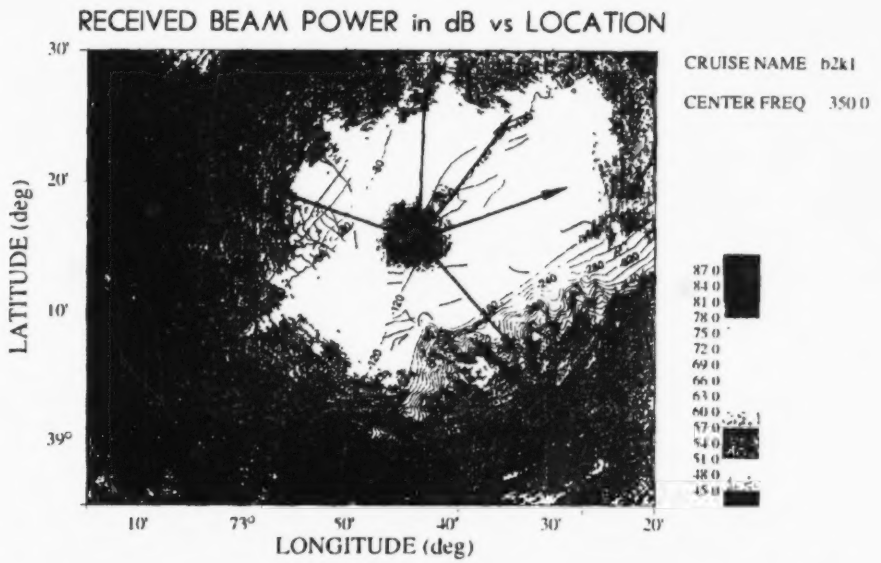

Fig. 1. Polar plot of the stacked reverberation on STRATAFORM from five 91 m SUS charges at Site S1' in the 350 Hz band. The black arrows indicate the array headings.

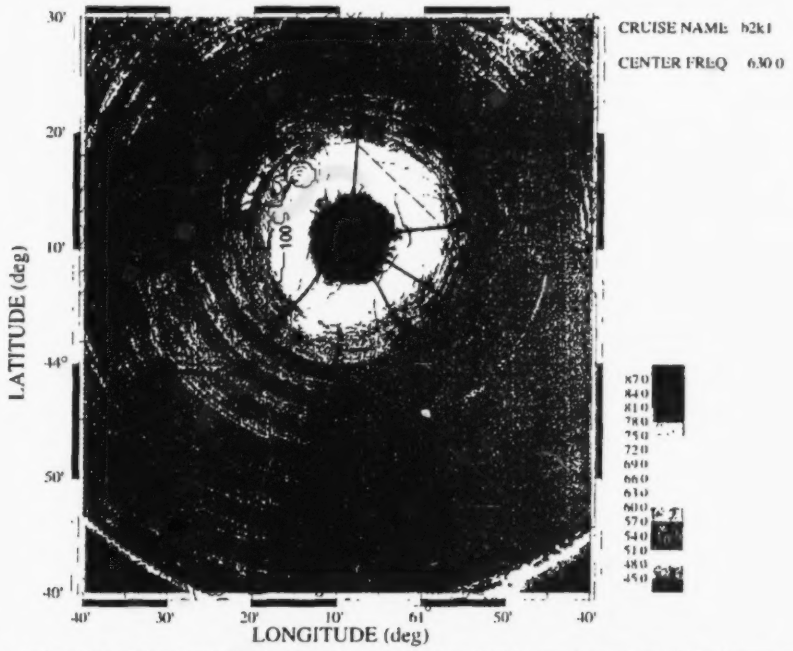

Fig. 2. Polar plot of the stacked reverberation on Scotian Shelf from five 18 m SUS charges at SiteC4 in the 630 Hz band. The black arrows indicate the array headings.

a bottom loss that would match the reverberation rate of decay Then, for the manual method, it is assumed model-and-match operation that is done manually in a single frequency band A range independence is assumed, along with very simple models of the bottom usually, a uniform fluid half-space (3 parameters) for the bottom loss, and Lambert's rule plus a facet term (3 parameters) for the scattering The manual procedure uses the best available *a priori* geologic information to start a search and, in absence of other information, starts with simple half space models of the bottom to extract seafloor information The model is first run to estimate the scattering strength vs grazing angle can be described as a Lambert's Rule, (sin-squared dependence) with the coefficient μ being slowly varied

The automated optimization technique is based on simulated annealing [9,10] in order to speed up the inversion process while greatly expanding the search space actually being tested The GSM model (range independent assumption) is still used as the forward model for reverberation The bottom loss is obtained using the ORCA code, an ARL-UT normal mode model capable of doing fast broadband computations It is a high fidelity research code that has been tested extensively Here, the ORCA model is used for the flexible bottom loss vs grazing angle module in it that permits bottom gradients The approach for this work is to use a multiple-frequency, geo-acoustically constrained simulated annealing search algorithm to test for model/data matches to towed array beam reverberation data vs time [1] The bottom types are initially divided into 1) clay-like, 2) silt-like, 3) sand-like, 4) limestone-like and 5) rock-like Then extensive use of Hamilton's relationships regarding depth dependence of key geo-acoustic parameters is made for each of these 5 types of material [11] The scattering strength kernel now is computed using the Mourad-Jackson model [12]

IV. Optimization results for boundary 2001

The new inversion algorithm was often run several times over multiple frequency bands Because of the greatly increased search capability of the automated algorithm and the appearance of more complicated frequency dependence in the reverberation data, it was decided to invert for a 2-layer model of the bottom The maximum number of iterations was set to 531 for these tests. Fig 3 shows a model/data comparison for site S1' (leg 2, event 1, array heading ~002°), for the best simulated annealing (SA) run (i e lowest Mean Square Error or MSE) after 531 model trials in the 630 Hz band Results for a multi-frequency inversion over three 50 Hz frequency bands (350, 630 & 800 Hz) are summarized in Table I The manual single layer single band result at 630 Hz from Ellis and Preston [13] is included as the next entry (the MSE for this result was only beaten by 7 realizations of one SA run) Note data after 20 s are ignored since the ambient noise begins to contaminate the incoherent reverberation data In the Site S1', SA result (first entry in Table I), the model for the top layer is 17 4 m thick with a compressional velocity at the top of 1635 and at the bottom of 1678 m/s, and with a velocity in the bottom half space of 1688 m/s (other parameters as noted) This is not inconsistent with the 2nd layer in preliminary estimates by Holland [14] for Site S1' (see last table entry) Also included in Table I are SA multi-frequency and 350 Hz manual single band results for the Scotian Shelf

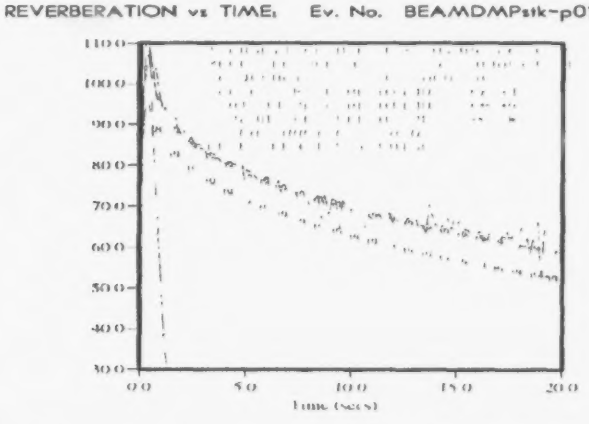

Fig. 3. Monostatic reverberation model/data comparison using GSM obtained via simulated annealing inversion for the best MSE result for data at Site S1' in the 630 Hz band (leg 2 event 1).

Bottom velocities from the SA results for site S1' are different from Holland's, but on average these different sets of parameters are fairly similar with respect to the effect on bottom loss at grazing angles below ~25°. Overall the SA algorithm and the manual method were very close but different than Holland's estimates for bottom velocity at site S1'. There were other SA solutions that were not as good as these sets but still gave good fits to the data. There is also fairly good agreement between the SA and manual results for the Scotian Shelf. However, at the latter site the SA results did not find a well-defined minimum in the cost function as it usually does. One possible explanation is that the water depth of 78 m may make the SA results less sensitive. Requiring consistency over frequency usually seems to improve the uniqueness problem that single frequency band inversions may have. One major limitation of this technique is that the area must be nearly range independent. Replacement of GSM by its successor, the CASS/GRAB model [15, 16] (now in progress), should improve the modeled reverberation estimates and hence improve inversion results for cases where range dependence is important.

Table 1. Inversion summary results by site for STRATAFORM site S1', and Scotian Shelf site C4 for two 2-layer Simulated Annealing (SA) cases, two 1-layer manual results and Holland's inversion near site S1'.

Result	Layer Depth (m)	Upper Compress Speed (m/s)	Lower Compress Speed (m/s)	Upper Density	Lower Density	Upper α (dB/m-kHz)	Lower α (dB/m-kHz)	MSE /SS Coef
S1'. SA-350 +630 +800	17.4	1635	1678	1.37	1.6	0.307	0.28	76.0
	∞	1688		1.67		0.399		/-33
S1'. Man.-630	∞	1650		1.7		0.5		83.0/ -32
C4 SA-350 +630 +800	14.7	1579.7	1599	1.46	1.52	0.364	0.369	128
	∞	1810		1.92		0.029		/-34
C4- Man.-350	∞	1606		1.7		0.6		NA/ -32
S1' Holland geo-inverse	6.2	1779.1	1779.1	~1.8	~1.8	NA	NA	NA
	12.3	1670.9		~1.8		NA		NA

V. Discussion and summary

A. Discussion

Our manual fit used 6 parameters, but often only 3 or 4 are significant in a shallow water environment. The automated inversion uses up to 11 parameters and achieves a better fit to the data. However, the significance of the parameters --especially the least sensitive ones -- is not always clear. In view of the variations in the above results, we could be inverting for parameters of an equivalent bottom model rather than for real properties. Chapman [17] has shown that some multi-parameter inversions can be shown to be consistent with an "equivalent fluid" model; i.e., the results are only sensitive to the low-angle part of the bottom loss curve. However, there is an inherent difference in seafloor penetration depth that is sensed by the different frequency bands used. If the bottom is changing rapidly with depth as Holland's detailed bottom measurement technique often shows, then one would expect the SA results to vary somewhat with frequency as different penetration depths sample different geology (and this is observed).

In conclusion, with simulated annealing one can get very good fits to the data, but probably can expect only to extract a few parameters that relate to bottom properties. A geoacoustic model with a gradient (i.e. the 2-layer model) seems to be better than the halfspace model used in the manual process on these data sets. The task of synthesizing a consistent physical bottom model when inverse results change with frequency requires

the multi-frequency optimization extension to the single band SA technique as was used here (a different type of broadband inversion was originally done in 1996 [18])

B. Summary of Long Range Reverberation Results

Polar plots from the towed array showed that important scattering features were observed from beyond the STRATAFORM shelf break.

SUS data in 50 Hz bands showed a bit more clutter-like returns from the Scotian Shelf than from the STRATAFORM but both sites showed anisotropy in the diffuse reverberation

The wide-area SA Inverse results were somewhat consistent with Holland's high-resolution localized results

All inversions were based on a broadside beam in three frequency bands from one selected heading, so all inversions should be repeated over more look directions and include beams other than broadside

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#517155 (8)

Some shallow water reverberation and bottom clutter observations near 400 Hz from the 2001 Geoclutter experiment

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Abstract Together with SACLANTCEN, MIT and NUWC, the author recently participated in a sea trial to measure shallow water bottom reverberation and geologically induced clutter in the STRATAFORM area off New Jersey. The 2001 Geoclutter experiment used monostatic and stationary bistatic coherent sources in a 50 Hz band near 400 Hz. The receiver was a 254 m, triple aperture towed horizontal array. Three representative sites in the STRATAFORM were selected and numerous ship tracks near these sites were run to break bearing ambiguity and help resolve range dependence. Data are presented as polar plots of received and matched filtered reverberation plus noise vs. position using mean sound speed to map time to range. Highlights of the reverberant returns are discussed. The STRATAFORM area is known to have benign surface morphology but contain many buried river channels. Results show some correlation of mapped sub-bottom features with the observed reverberation. Also noted is that this area shows a large amount of clutter in the reverberant returns that does not correlate with any known surficial or sub-seafloor features. Reverberation measurements using SUS were made immediately following the Geoclutter experiment during the Boundary 2001 experiment. Some comparisons of the Geoclutter and SUS results are discussed. Work was Supported by ONR Code 321OA, Grant N00014-97-1-1034.

I. Introduction

It has been noticed by many that shallow water low-frequency (<5 kHz) reverberation often can contain display clutter i.e. target-like returns from the ocean bottom. Often the clutter is observed even when large bathymetric features are absent. The medium-range reverberation measurements and analysis were recently conducted during the May 2001 Geoclutter Experiment sponsored by ONR. This was a joint research effort involving SACLANTCEN and it's R/V ALLIANCE together with MIT, ARL-PSU, and NUWC researchers from the US. SPAWAR-SSC and NFESC, provided a moored bistatic source courtesy of the MACE program office at ONR, WHOI set the moorings and URI ran the R/V Endeavor (a UNOLS vessel). This experiment was designed to improve our understanding of the physical mechanisms which scatter incident energy from on or below the seafloor into a receiver and which can possess target-like characteristics (clutter). Other goals were to improve the understanding of the effects of sediment composition on clutter and reverberation, improve the understanding of the effects of surface morphology and composition on scattering and clutter, and assess the suitability of current high fidelity reverberation and scattering models for model/data comparison and prediction. The STRATAFORM area off New Jersey was selected because of the high resolution geo-acoustic data that has already been collected there, because the area is known to contain buried river channels and other sub-seafloor features that may give rise to clutter, and because it is representative of continental-shelf shallow-water areas. This paper briefly discusses some reverberation results for this experiment. Significantly more preliminary results and a full discussion of the experiment details can be found in the Geoclutter Cruise Report [1].

II. Sample reverberation observations

A. Overview

Extensive oceanographic and transmission loss measurements were also made as part of the sea trial. Reverberation measurements were carried out using a towed horizontal line array (HLA) in conjunction with a towed source for monostatic measurements and a moored source for bistatic measurements. The R/V ENDEAVOR deployed and operated the bistatic source consisting of a moored vertical array of seven XF-4 transducers. The primary equipment for the monostatic reverberation measurements were 2 Mod 40 flextensional sources deployed by SACLANTCEN's R/V ALLIANCE, and its HLA, the 254 m, three-aperture Prakla low-frequency array with design frequencies of 375, 750 and 1500 Hz. Signals used for both monostatic and bistatic measurements were LFMs and CWs contained in the 370 to 450 Hz band. Multiple tow directions are necessary to resolve the left-right ambiguity of the line array so tracks were often paired with offset headings typically between 15° and 30°. The array was deployed and towed at a speed of 4 to 5 kn. After a turn, the arrays were allowed to stabilize (about 10 min), after which monostatic and bistatic coherent pulses were transmitted to make reverberation measurements. Track legs were often 10 km in length so the time required for each leg of the experiment was typically about 1 1/4 hours, plus at least 15 minutes time required on the turns, (typical turning angle was ~210°).

Fig 1 shows all the ship tracks (in green) Fig 1 Also shows the STRATAFORM bathymetry, the buried river channels (in black), sub-bottom horizons (in red) and small surficial features like iceberg scours (in blue) all provided by Goff [2] The bathymetry structure was mapped to resolutions of about 30 m over the STRATAFORM Further details of the receiving arrays and the ARL-PSU data acquisition, processing and display descriptions are in [3 -5] Time domain Beamforming and signal basebanding was done in software using algorithms developed by SACLANTCEN's R Hollett

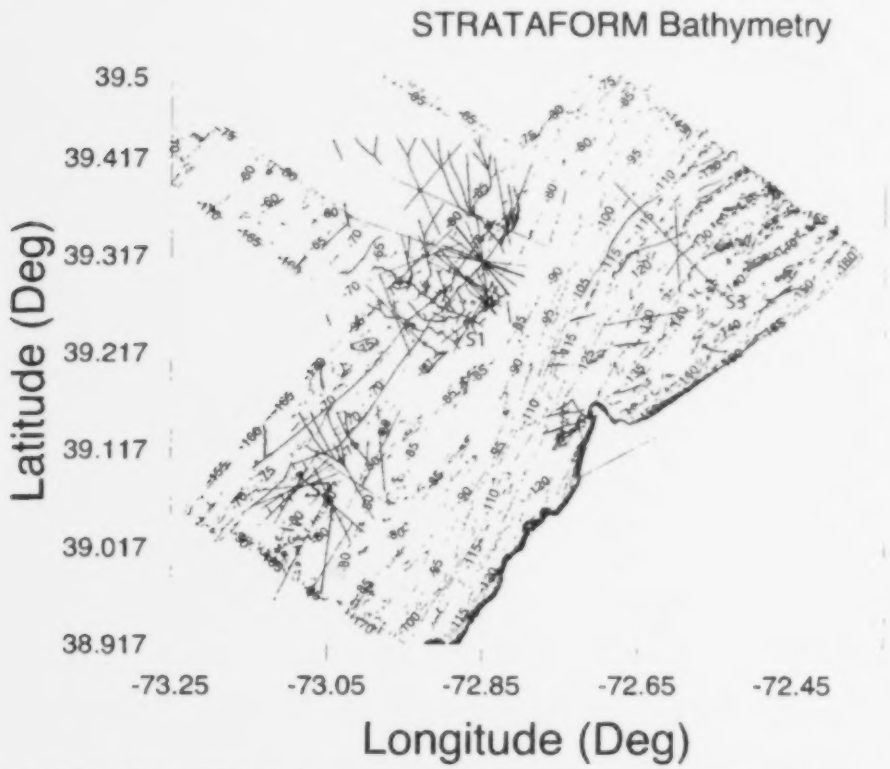

Fig. 1. Map of STRATAFORM bathymetry and Geoclutter ship tracks (green lines), buried river channels (black dendritic lines), sub-bottom horizons(red) and small topographic features (blue)[2].

B Sample Reverberation from STRATAFORM

The first example of this section describes reverberation from a ping near N 39° 05' and E 73° 05' at a site called S2 Water depth was about 70–75 m Data from the Prakla array were usually recorded for 90 s for bistatic events and for 50 s for monostatic ones The sound speed was near 1484 m/s at the surface, with a very weak sound channel axis and a sound speed minimum of ~1475 m/s at a depth of ~ 35 m at this site The Prakla array was deployed to a nominal depth of 46 m Winds were fairly light the logs show a Beaufort wind force ~2-3 Directional background noise was often present but ship traffic seemed to be moderate

Fig 2 shows a polar display of matched filtered bistatic reverberation from the STRATAFORM site S2, on a towed array in a 50 Hz band centered at 420 Hz from a 1 s LFM ping Reverberation is color-coded vs intensity and time is mapped bistatically into location Fig 2 also contains the STRATAFORM bathymetry

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and other features as before Since this is a single ping the data contain the array ambiguity i e there is a mirror image about array heading that is distorted in the bistatic displays Directional ambient noise (usually shipping) above the average background noise is seen as radials from the array in the plot In this case most higher-level noise is coming from near forward and aft endfire directions Strong anisotropic scattering is usually associated with bathymetric features Strong scattering can be clearly seen from the large orange colored splotches running from SW to NE between the 80 m contours and due south of the source receiver ellipse Looks at other pings shows that the area just described and not its mirror image is the source of the high backscatter There is no obvious bottom or sub-bottom feature indicated near these splotches Although not visible at the size of Fig 2 shown here, there is a clear reflection from the R/V Endeavor that is visible for this event Also, there are two closely spaced BBN reflectors ~8 km due south of the source that also give a nice reflection in this event(shown as two open triangles (^^) near an 80 m label)

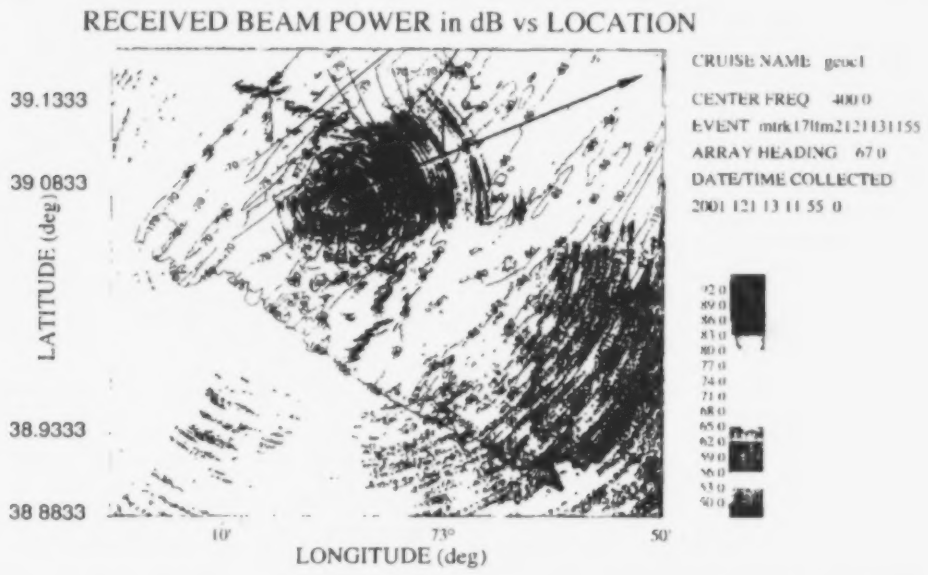

Fig. 2. Polar plot of the bistatic matched filtered reverberation at Site S2 on STRATAFORM using a 1s LFM from 390–440 Hz. The black arrow direction indicates the array heading, the base of the arrow the array position, and the tip of the long thin triangle shows the location of the bistatic source.

The second example of this section describes reverberation from a ping near N 39° 55' and E 72° 40' at a site called S1 Water depths ranged from ~70–85 m The sound speed was more variable but near 1485 m/s at the surface, with a moderate to strong sound channel axis and a sound speed minimum of ~1474 m/s at a depth of ~ 40 m at this site The Prakla array was deployed to a nominal depth of 32 m Winds were moderate the logs show a Beaufort wind force ~3-4 Directional background noise was often present but ship traffic seemed to be moderate

Figure 3 below shows the polar display of this matched filtered bistatic reverberation event from the site S1 on the towed array in a 50 Hz band centered at 420 Hz from a 2 s LFM ping As before, reverberation is color-coded vs intensity and time is mapped bistatically into location Fig 3 also contains the STRATAFORM bathymetry and other features as before Ambient noise (shipping) above the average background noise is seen as radials from the array in the plot As above, this is a single ping so the data contain the array ambiguity i e there is a mirror image about array heading that is distorted in the bistatic displays There is some good correlation between some clutter returns and the R reflectors along the 65 and 70 m contours near the center of Fig 3 There is also good correlation between some of the clutter and the buried river channels SW of the

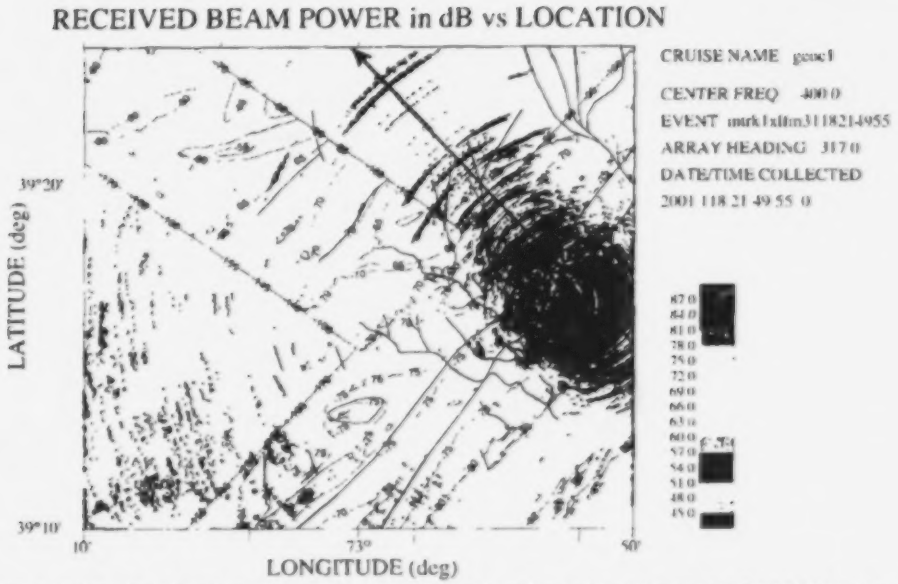

Fig. 3. Polar plot of the bistatic matched filtered reverberation at Site S1 on STRATAFORM using a 2s LFM from 390-440 Hz. The black arrow indicates the array heading, the base of the arrow the array position, and the tip of the long thin triangle in the ellipses shows the location of the bistatic source.

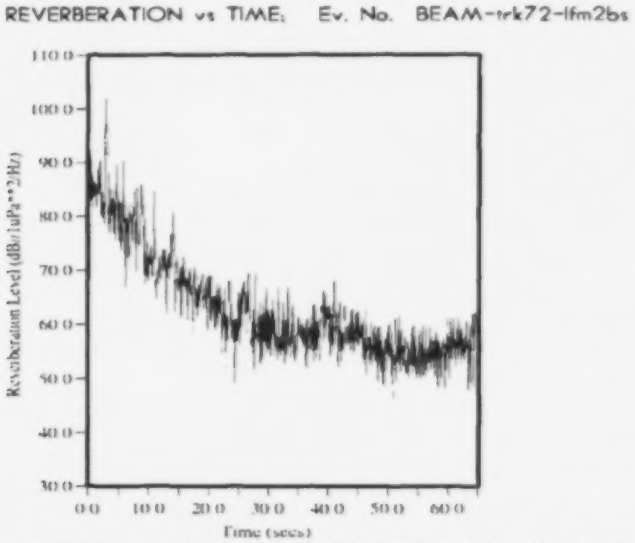

Fig. 4. Monostatic reverberation sample from the 1s LFM near Site S1 showing the spikey character typical of the area.

source – receiver ellipse (the lineated returns that follow the channels) Clearly there are other clutter returns that are not well mapped to any currently known features. Finally, Fig 4 shows a broadside beam time series from another ping originating to the northwest of S1 This is very typical of beam time series results for this experiment and shows the spikey nature of the clutter observed at all 3 sites on the STRATAFORM (site 3 results not shown here)

III. Discussion and Summary

A *Discussion of coherent pulse results to date*

Strong clutter like returns we seen generally from sites 1, 2 and 3 in the STRATAFORM using matched filtered coherent pulses Results from SUS in the same area indicate that the STRATAFORM is not a particularly high clutter area compared to other REA areas like the Malta Plateau, the Scotian Shelf or Kiparissia Bay when using the REA SUS processingtechniques [3,5,6] This seems to imply that many other REA areas will be even worse than the STRATAFORM with respect to clutter when coherent pulses are used The high clutter sometimes correlates with parts of buried features like sections of the river channels and sections of the R-reflectors. Other high clutter returns seem uncorrelated with any known features, be it surficial or sub-seafloor, but much of the area is still not mapped in the detail that is needed A very preliminary observation is that there does not seem to be a good correlation of clutter with the iceberg scours (~1 m relief) or blowout pits (~5-m relief)

B Summary of Broadband Reverberation Observations Using SUS From Boundary 2001 Experiment [6]

Polar plots from the towed array showed that important scattering features were observed from beyond the STRATAFORM shelf break

SUS data in 50 Hz bands showed a bit more clutter-like returns from the Scotian Shelf than from the STRATAFORM but both sites showed anisotropy in the diffuse reverberation

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Acoustic Monitoring of Sources and Excitation of the Acoustic Channel during Geoclutter 2001

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Abstract

The Geoclutter 2001 sea trials were comprised of a large number of transmitted waveforms that were used to probe the shallow underwater acoustic channel, bottom and subbottom Investigation of the associated acoustic signatures should prove useful for characterizing specific geologic features, clutter and reverberant background interference. The ultimate aim is to improve detection/classification and reduce false alarms. In this analysis, we take a close look at the acoustic signatures from selected pings recorded on the hydrophones deployed from R/V Endeavor in Geoclutter 2001 The data presented are part of a larger data set, which can be utilized in estimating the range-dependent propagation and channel characteristics from Alliance to Endeavor throughout the conduct of the experiments From the geoclutter (selected pings) and from a related shallow water sea trial conducted in March 2000, LWAD 00-1, particular attention is given to analysis of the nonlinearities in the acoustic response arising from both the excitation waveform and the propagation medium, without specific characterization of the causes of the nonlinearities.

1. Introduction

The Geoclutter 2001 acoustics experiment provided numerous opportunities to examine the acoustic response of the shallow water channel in the New Jersey Strataform area The ultimate purpose is to determine the causes of geologic "clutter" at low frequencies in shallow water Two ships participated, the R/V Endeavor and the NRV Alliance. Endeavor acted as the bistatic source platform, utilizing vertical source array of 7 XF-4 transducers while at moorings at three sites, and was also equipped with an acoustic monitor hydrophone Alliance was a monostatic source and receiver ship, utilizing a single XF-4 transducer towed source and an extended hydrophone line array with realtime beamforming and matched filter capability

In this paper we concentrate on a few of the acoustic data from the monitor hydrophone on board R/V Endeavor We present results of examining the at-sea calibration source calibration efforts, and preliminary comparisons of the signals measured from both the ships at site 2, where transmission loss and channel measurements are briefly discussed Comparisons also are made with collections from a related shallow water sea test [1]

2. Representative Test Geometry

Figure 1 shows the measurement location relative to potential geologic clutter features and previous measurements. R/V Endeavor source position is shown as a symbol called "source" Alliance is 5 9 km SE of Endeavor's location, heading NNW The red ellipse corresponds to the end of direct blast blanking time, the blue ellipse to the time of the arrivals expected at Alliance from the "Prism" BBN acoustic reflectors. The "cross" near AMCOR site 6010 corresponds to the location of the Hudson Canyon acoustic experiments [2].

3. Acoustic Source Measurements (Time Series and Power Spectrum)

The table below gives a sample representation with associated figures of selected in-water acoustic sources deployed by Endeavor and Alliance as seen by the reference hydrophone (F37) deployed from Endeavor These data were collected during the first leg of Day 3 of the testing at Site 2 Following the table, an explanation of each figure is given

Figure No.	Research Vessel	Wavetrain	Description
2	Endeavor	wtcw-2	Time Series
3a,b	Endeavor	wtcw-2	Power Spectrum
4	Endeavor	wtlfm-3	Time Series
5a,b	Endeavor	wtlfm-3	Power Spectrum
6a,b	Alliance	wtcw-2	Power Spectrum
7a,b,c,d	Alliance	wtlfm-3	Power Spectrum

Figure 2 shows the measured time series of the acoustic source deployed from Endeavor, while the center of the (MACE) active source array was placed at 180 5 feet and the F37 receive hydrophone on Endeavor was at a depth of 150 ft The source and receiver were separated in range by approximately 118 feet, the MACE being situated at the bow and the F37 aft on the port side The signal is a 0 5 second seven stepped CW wavetrain, Hann shaded, at 385, 405, 425, 395, 415, 435, and 370 Hz The time series data were obtained at a sampling rate of 100 kHz

Figure 3a shows the corresponding spectrum for the time series shown in Figure 2. There are a large number of harmonics that dominate the spectrum Figure 3b provides an enlarged view of the fundamental frequencies and strong second and third harmonics. The seven stepped frequencies are clearly observable in both the fundamental and harmonic structure

Figure 4 shows the time sequence of data points for a 2 second LFM wavetrain with Tukey shading from 390-440 Hz The data were sampled at a rate of 100kHz

Figure 5a provides the corresponding spectrum for the time series shown in Figure 4 Note the large number of harmonics present in the spectrum, eight of which are 10-20 dB or more above the background level. Figure 5b shows an expanded view of the fundamental frequencies (390 to 440 Hz) and their second harmonics

Figures 6 and 7 show the acoustic spectra of Alliance's acoustic radiated source measured by Endeavor's F37 reference receiver The range between source and receiver at time of collection was approximately 5 9 kilometers.

Figure 6a shows the full spectrum of Alliance's stepped CW transmission Figure 6b shows the detail of the main transmission band The CW shows two strong high order harmonics

Figure 7 shows detailed spectral plots of the LFM from the Alliance source as received from Endeavor's F37 reference phone. "7a" is the full spectrum, "7b" the main transmission band, "7c" the first prominent harmonic, and "7d" the second prominent harmonic. It is interesting to note that just as was the case for the CW, the LFM spectrum also shows a prominent 9th harmonic.

4 Estimate of Measured Transmission Loss

From the received measured levels of the Alliance and Endeavor acoustic sources using Endeavor's F37 reference hydrophone and from the calibrated estimate of each source level, one is able to obtain an estimate of the measured transmission loss for the time and range at which the source measurements are taken For example, at a range of approximately 118 feet, representative spectral levels from the Endeavor's source are shown in Figure 5 for an LFM wavetrain near 400 Hz. During the same time period, measurements of the same wavetrain were collected by Endeavor from Alliance's source, at a range of 5 9 km These spectral measurements are shown in Figure 7 One first computes the relative difference in receive level between the two sources, namely 32 dB for the present case Then one must account for the 10

dB difference in source levels between the two emitting research vessels (i e , 222 dB - 212 dB) One must also consider the spreading loss between Endeavor's acoustic source and reference phone (i e , 118 feet estimated) that equates to a loss of approximately 32 dB Subtracting this number from 222 dB provides an effective absolute receive level as seen by the F37 Hence, a signal level of 190 dB re 1 micropascal can be viewed as a calibration level to be compared with the F37 measurement of Alliance's attenuated source level The received (attenuated) level computes to be 158 dB (i e , 190dB - 32 dB) Since transmission loss is computed from the following formula, one obtains:

Transmission Loss (TL) = Radiated Source Level (SL) - Received Level (RL)

TL = 212 dB - 158 dB

= 54 dB (at 5 9 kilometers)

Measured estimates of transmission loss can be used as "tie points" to affix to and compare with other related measurements and/or acoustic propagation models For example, the measured estimates from Geoclutter 2001 were found to be generally in good agreement with modeled predictions obtained in a related shallow water test across similar ranges and frequencies of interest [3]

5 Estimation of Channel Effects

A comparison of Figures 5b and 7b also gives an estimate of channel effects in the band of the LFM transmission between Alliance and Endeavor The relatively full band spectral levels of the direct path measurement may be compared with the deep nulls occurring within the band corresponding to the hydrophone measurements The full transfer function may be possible to be derived as well, which holds the promise of providing estimates of the acoustic channel response for all transmissions performed from Alliance while Endeavor was at mooring, and may be compared to detailed models of the acoustic propagation medium to be investigated by other Geoclutter participants.

5 1 Nonlinearity Arising from the Propagation Medium

A significant number of harmonics have been observed in the data received from both Endeavor and Alliance acoustic sources Since the Alliance monitored her source responses in the band of excitation, it is not possible to claim with any certainty the origin of the harmonics picked up by the Endeavor distant receiver 5 9 km away. On the other hand, it is highly likely that the harmonics emanating from the Endeavor source as seen by Endeavor's receiver separated by only 118 feet, result from "overdriving" the source at high amplitude levels The "overdriving" of the MACE source at approximately 222 dB re 1 micropascal @ 1 meter is conjectured to be the principal cause of the harmonics observed in the receive spectrum

One can contrast this result with a very different result obtained in another shallow water sea test, in which no appreciable excitation-induced nonlinearity was present, yet the measured signal received from a distant source, showed significant harmonics that could only be properly attributed to interactions with the acoustic channel [1] Figure 8 shows a representative spectrum of an LFM in-water signal without harmonics picked up by a receiver approximately 20 meters from the radiating source Figure 9 shows a representative acoustic spectrum with visible harmonics from data collected at a receiver 7 4 kilometers from the source after passing through the acoustic channel Figure 10 shows a representative spectrum of a model fit to the measured time series This fit is based on a second order convolution of the excitation waveform with the acoustic propagation channel using a Volterra series integral expansion. Clear quantitative agreement was found between the model fit and measured time series data in this early assessment leading to the conclusion that the nonlinearity at the receiver was induced not by the

radiating acoustic source alone, but rather by its interaction with the medium as it propagates through the acoustic channel [1] However, the source of the channel-induced nonlinearity, to date, still remains an open question

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[2] Carey, W , Doutt, J , Dillman, L M , and Evans, R 1993 "Shallow Water Transmission measurements taken on New Jersey Continental Shelf," SACLANTCENTRE Conference proceedings 42(1), August 1993, NATO Unclassified

[3] Gomes, B R , Fisher, R A , Fulford, J K , Nero, R W , Love, R H , "Environmental Characterization for the Littoral Warfare Advanced Development 00-1 Experiment," NRL Memorandum Report 7180--00--8249, Naval Research Laboratory, Stennis Space Center, MS, 30 October 2000

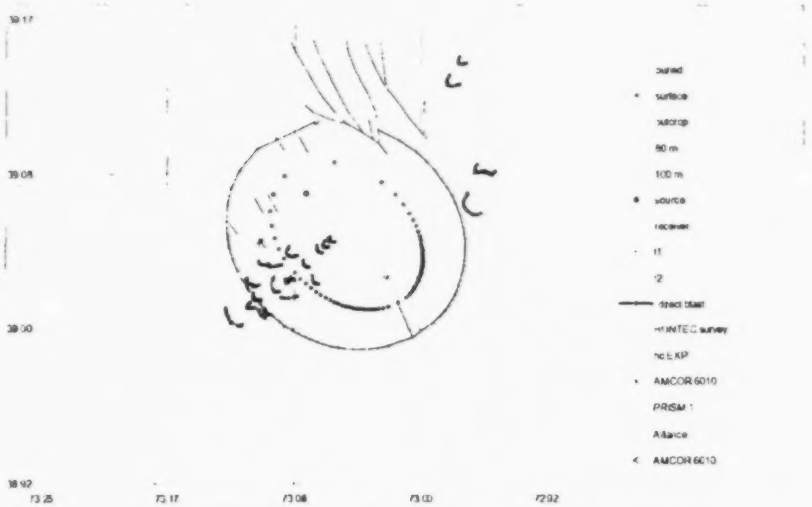

Figure 1 Representative measurement geometry (site 2)

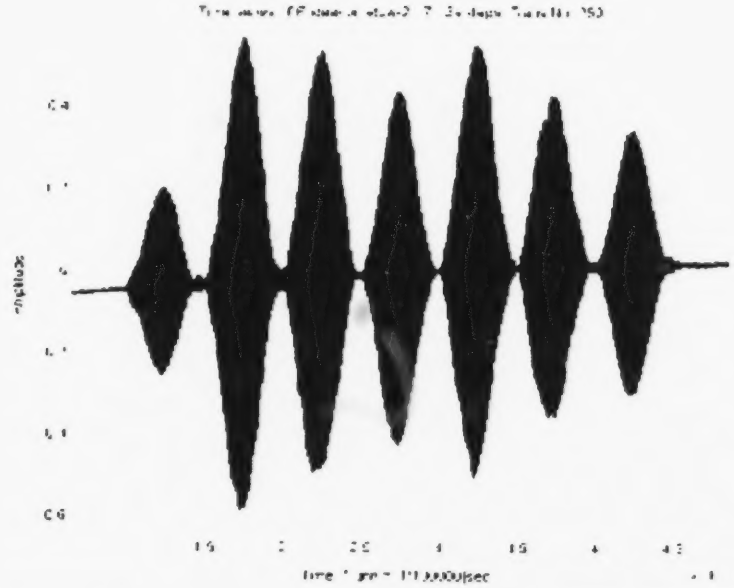

Figure 2 Representative Endeavor seven-stepped CW (in-water) time series

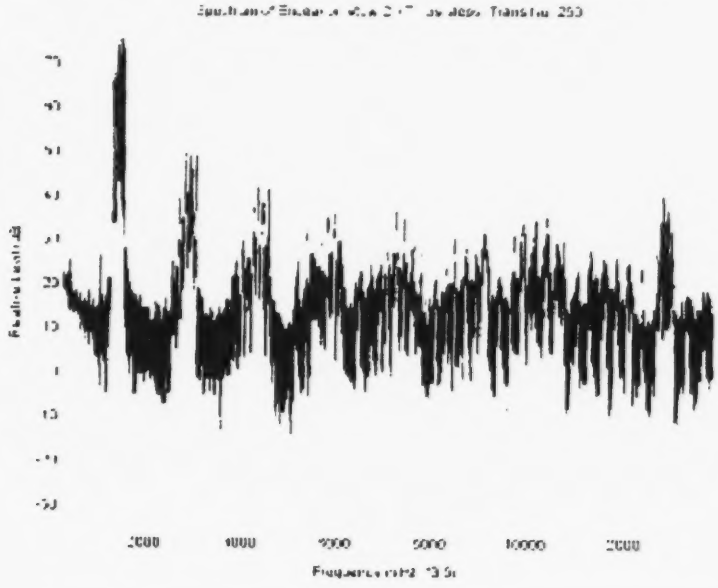

Figure 3a Representative Endeavor seven-stepped CW power spectrum

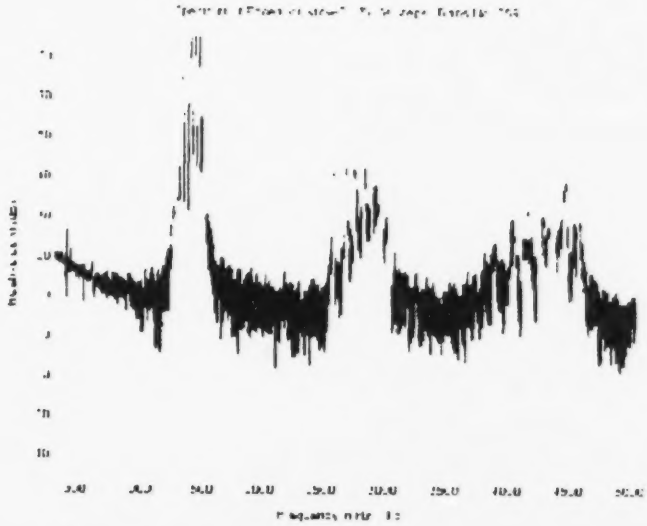

Figure 3b Amplified view of fundamental, second and third harmonic frequency components shown in Figure 3a

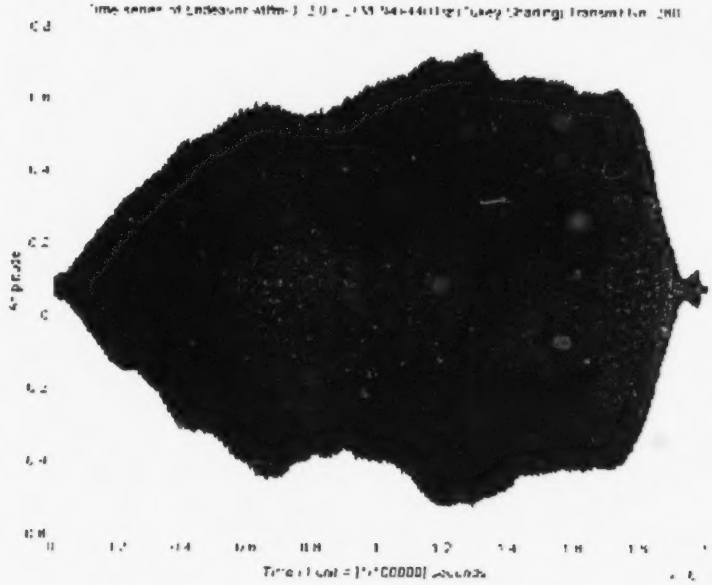

Figure 4 Representative LFM (in-water) time series

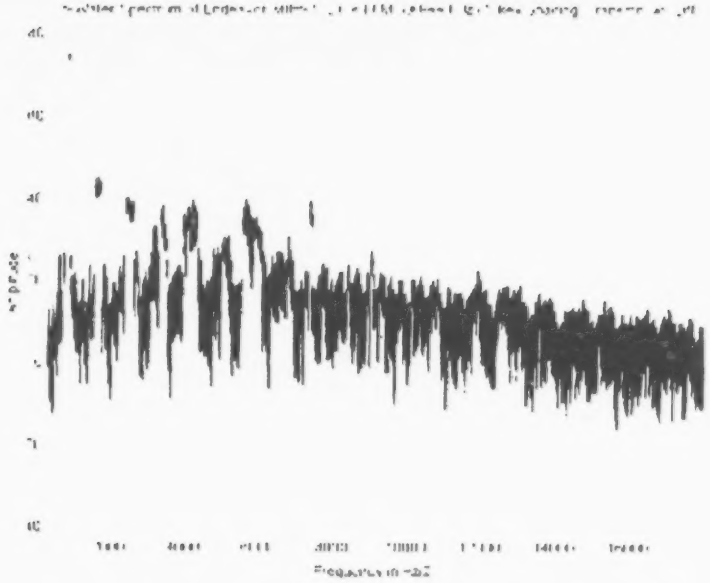

Figure 5a Representative Endeavor LFM (in-water) power spectrum

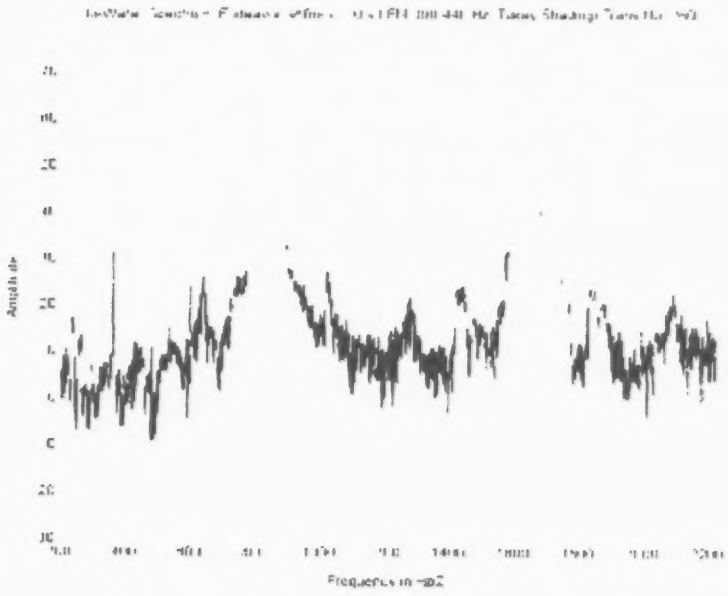

Figure 5b Amplified view of segment shown in Figure 5a

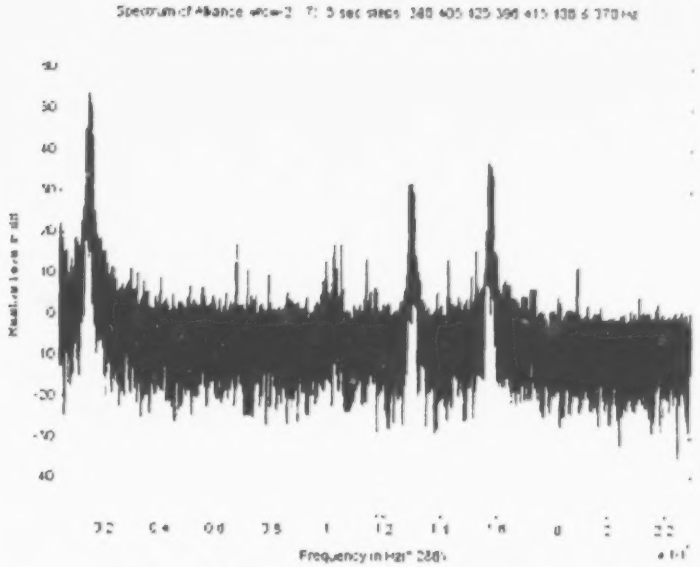

Figure 6a Representative Alliance seven-stepped CW (in-water) power spectrum as observed from Endeavor's F37 reference phone at a distance of about 5 9 kilometers

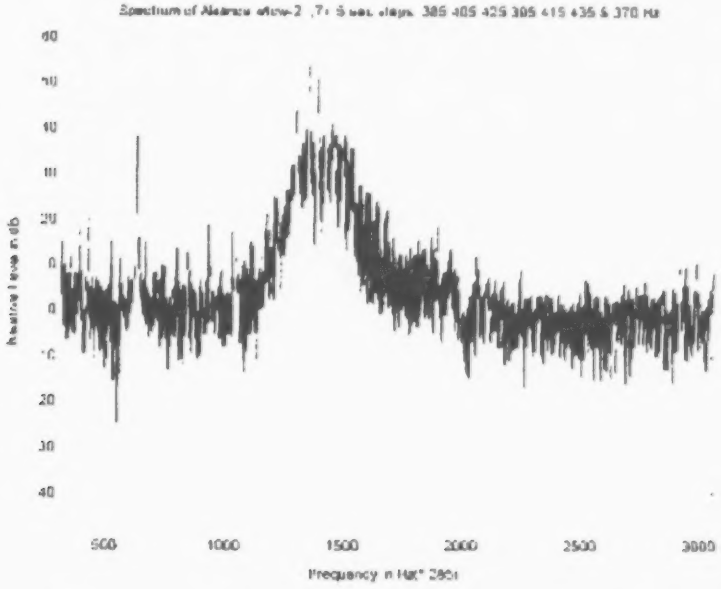

Figure 6b Amplification of fundamental frequency components shown in Figure 6a

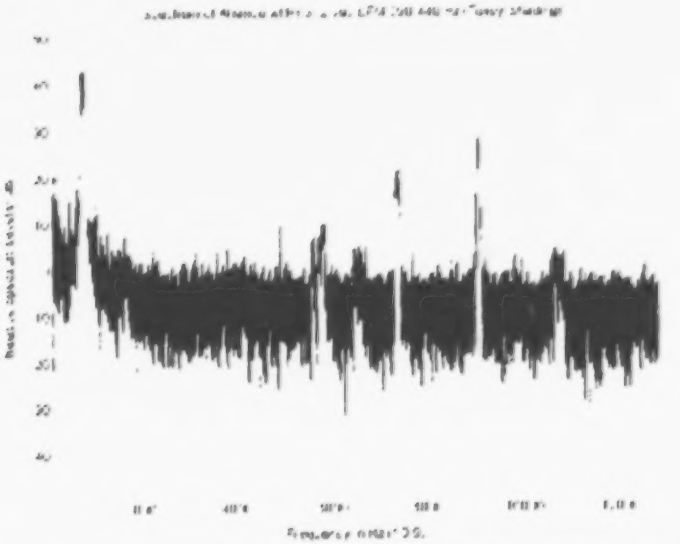

Figure 7a Representative Alliance LFM (in-water) power spectrum as observed from Endeavor's F37 reference phone at a distance of about 5 9 km

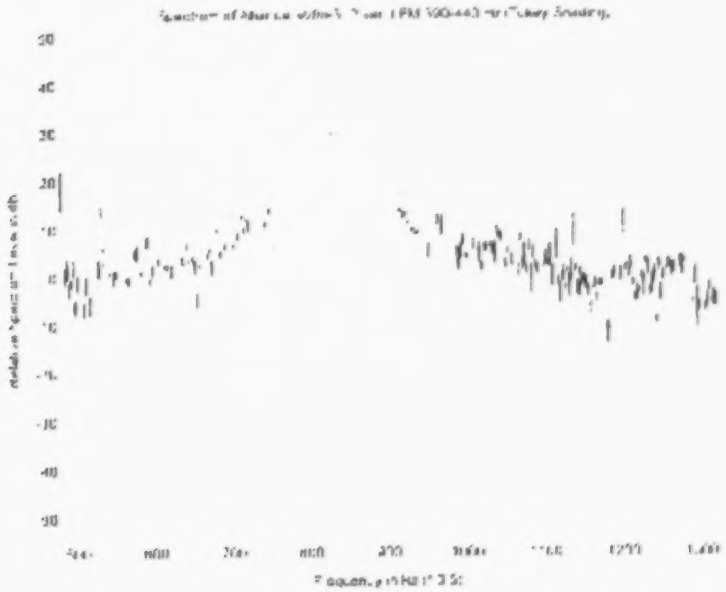

Figure 7b Amplification of the fundamental frequencies shown in Figure 7a

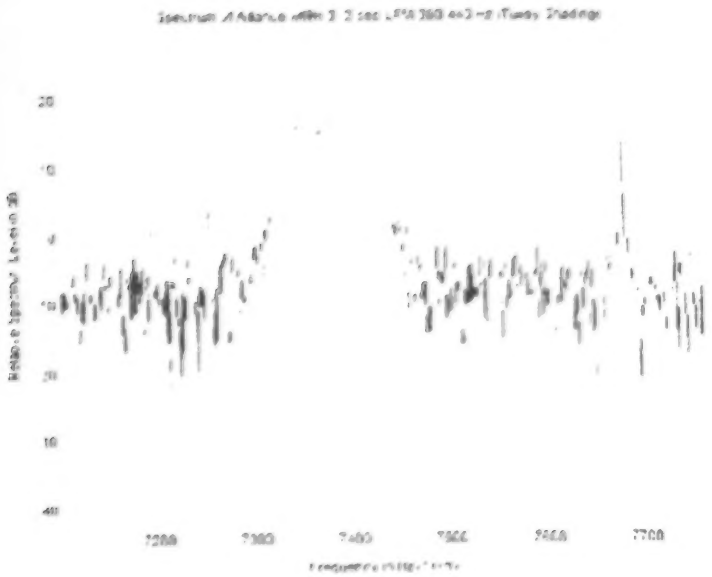

Figure 7c Amplification of first prominent harmonic shown in figure 7a

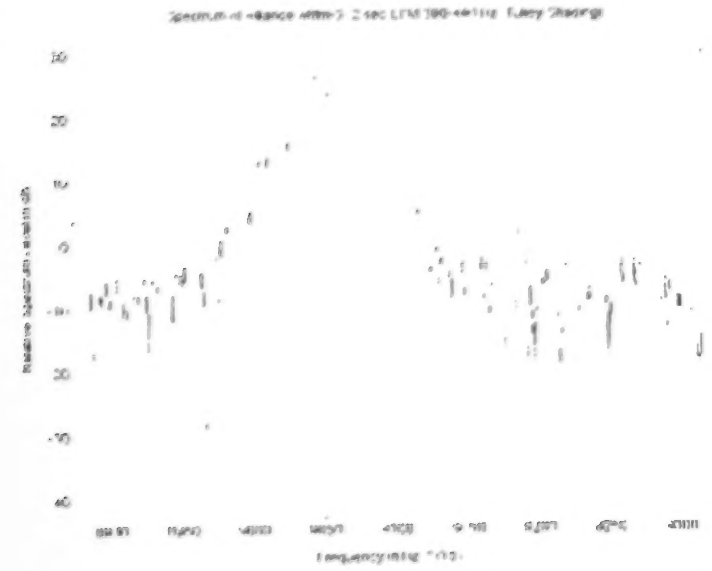

Figure 7d Amplification of second prominent harmonic shown in Figure 7a.

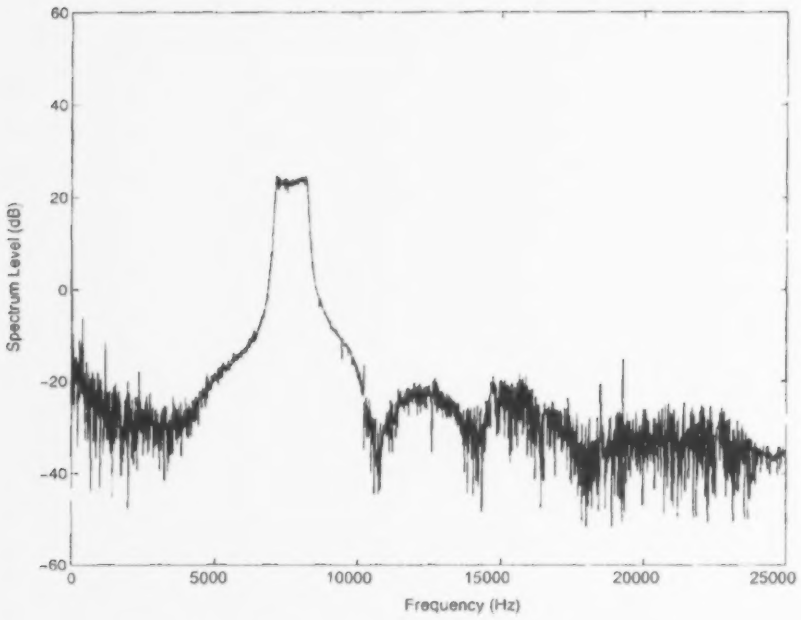

Figure 8. Representative CPPP Transmit Spectrum for LFM Waveform

(In-Water Spectrum as Seen by Receiver 65 Feet from Source)

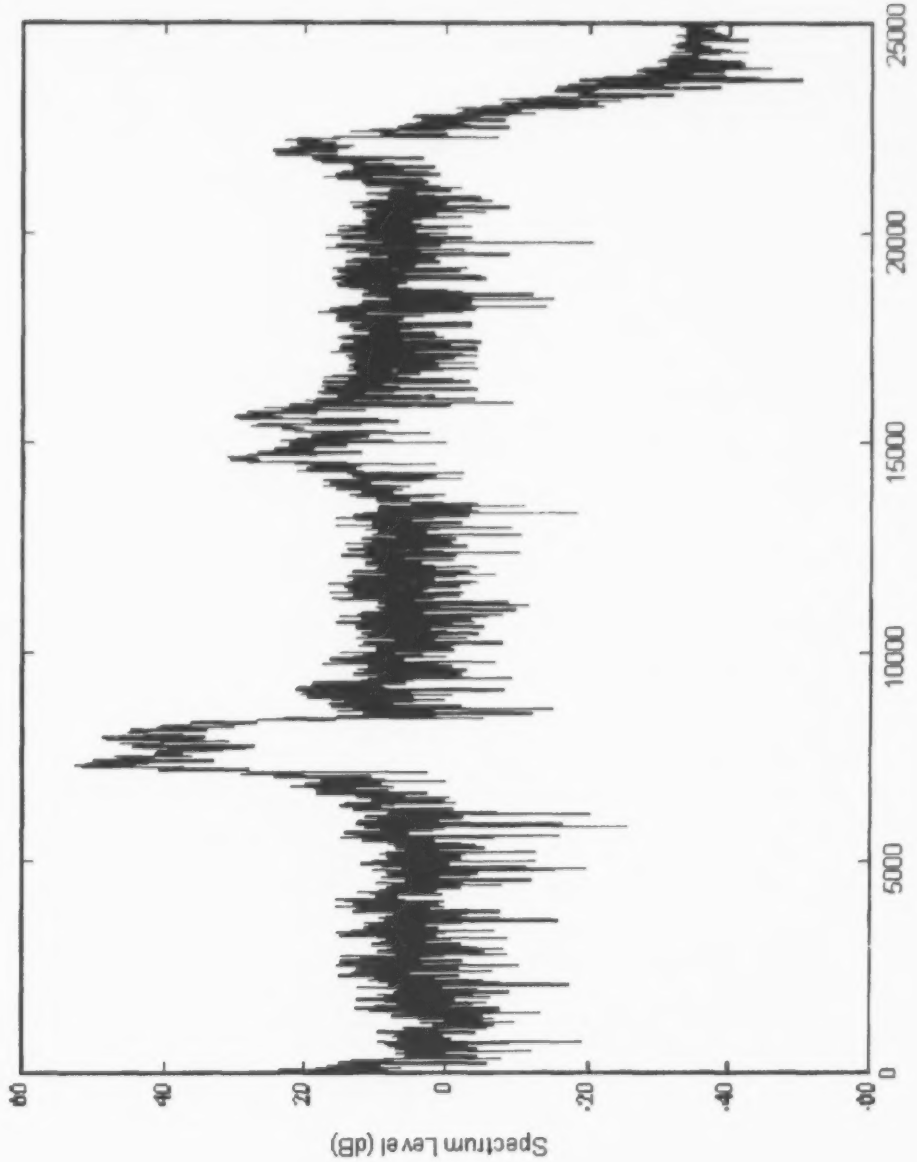

Figure 9. Representative CPPP Receive Spectrum for LFM Waveform (Spectrum Picked up by Receiver 4 mm from Acoustic Source)

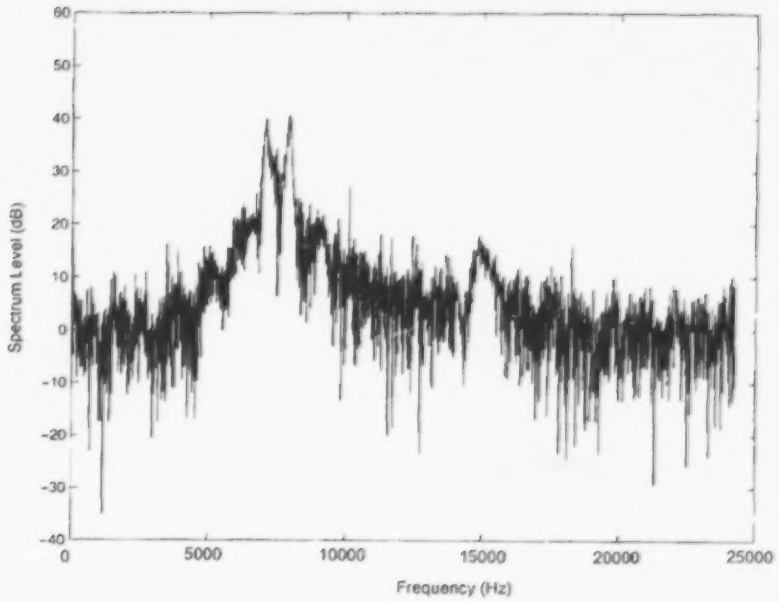

Figure 10 Spectrum of Volterra Second-Order Fit to Measured Time Series

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Predicting the Distribution and Properties of Buried Submarine Topography On Continental Shelves

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Introduction

A major goal of the U.S. Office of Naval Research is to reduce or mitigate geologic clutter observed on fleet sonar systems. Geological structures just beneath the seafloor, with high-angle reflecting surfaces, can return false sonar alarms. Examples include steep-walled channels from buried paleo-river valleys or iceberg furrows. The environmental research goal then is to develop numerical models and approaches to predict the distribution and properties of subsurface features hypothesized to be responsible for sonar geoclutter. The geological premise is that during a sea level rise paleotopography will either be removed or buried. Channels are important because of the acoustic reverberation related to these buried features. Two issues define the problem. The landscape forming issue includes where geoclutter features occur on world margins and what are their characteristics, i.e. channel orientation. The landscape burial issue is to understand whether the geoclutter features will be exposed or buried. In some areas the channels, for example, would be deeply buried, in other locations the channels will be buried but near the seafloor. The features could be even exposed at the seafloor. The problem is predicated on the Navy being able to sense real Doppler targets from false geoclutter targets particularly in nearly flat continental shelf areas. While this project is in the beginning phases, this paper provides an overview of the approach to this complex problem.

Background

Accommodation is critical to the amount of erosion and sediment delivery to an adjacent continental margin. Terrestrial accommodation is created or destroyed when the top of the fluvial/coastal plain system subsides below or is uplifted above the "theoretical equilibrium profile", defined as a graded or dynamic surface upon which there is no net sediment accumulation or erosion (Mackin, 1948; Posamentier et al., 1988; Schumm, 1991). The effect of base (sea) level change on fluvial systems depends upon factors such as rate of change, amount of change, direction of change, river character, and dynamics and erodibility of the sediment source area.

Aggradation or down cutting are not the only fluvial responses to changes in base level. Depending on its morphology, a river may be able to adjust its pattern and shape (e.g., sinuosity) in order to accommodate a base level change. Uplift of the coastal plain may enhance fluvial erosion (e.g., Posamentier et al., 1988), or it may create a drainage barrier

leading to the formation of wetlands and marshes. If there is any change to the base (sea) level, the landform must respond by adjusting its stream profile, often as an erosion front that propagates (nick point migration) up a fluvial network.

The rate of nick point migration depends upon the substrate character and hinterland morphology. If the nick point has migrated out of the region influenced by the ensuing base level rise, then associated erosion will regrade the equilibrium profile and supply sediment to the margin. The fluvial network's response to a base level fall depends on the drainage physiography with respect to the submerged continental shelf (Shanley and McCabe, 1994). If the slope of the exposed shelf is less than that of the fluvial system, aggradation will occur in the lower reaches of the fluvial system. Conversely, if the slope is greater, then erosion will occur at the change in slope and systematically migrate upstream. Finally, if the slope is similar to the fluvial system, then aggradation or erosional down cutting will not occur.

Channel features incised into the shelf during the last sea level low-stand are not apparent on many modern continental shelves. Depositional processes during and subsequent to the period of sea-level rise have filled the channels and created a surface morphology that is often independent of the former low-stand surface. The relationship between the buried channels and the modern seafloor is the product of both terrestrial sediment input to the marine system and the transport processes operating on the continental shelf. Together these determine the rate and spatial pattern of deposition and consequently the depth of burial of low-stand features

As sea level rises, channels on the low-stand surface pass through a range of environments ranging from the high-energy, sandy nearshore to the low-energy muddy offshore. To model the acoustic scattering of buried channel features, it is necessary to know how deeply the channels are buried and the nature of the channel fill (e.g., sand or mud). The characteristics of the channel fill and the rate of filling depend on the rate of sea-level rise, i.e., the speed with which the exposed shelf surface passes through these regimes as sea level rises. One of the most dynamically complex sedimentary environments on short time scales is the nearshore/beach. The high-energy conditions that characterize this environment are capable of significant reworking of older surface deposits, including removal of fine-grained sediment and smoothing of preexisting topography. In addition, the balance between the supply of sand and coarser sediment to this region and its redistribution and removal during storms is an important control on coastal morphology.

Numerical and Data Approach: Patterns of shelf dissection

A spatially and temporally explicit simulation model (Howard, 1994; 1997, 1999) is used to predict coastal shelf dissection through incorporation of weathering of exposed rock, mass movement by creep, fluvial erosion and sedimentation, and groundwater sapping. The model has been used to simulate steady state landscapes, incision of exposed surfaces, fault-block dissection with alluvial fans, deltas, and gullies. The model produces explicit topographic digital elevation maps (DEMs) of simulated landforms, and

predicted depths of sedimentary fills. Associate models simulate channel morphology and floodplain development (Howard, 1996), bed topography in meandering channels (Johannesson and Parker, 1989), lateral migration, loop cutoff, floodplain deposition, and braided streams and deltas development.

A series of computational experiments were conducted to explore the various controls on density and depth of channel incision: the shelf geometry (width and gradient), topographic features (beach ridges), the rate of sea level lowering, tectonic deformation including isostatic rebound, shelf material (grain size, cohesion, bedrock), and location and size of upland rivers. Inflowing upland rivers are modeled in profile and coupled with a spatially explicit continental-shelf grid at the landward mesh boundary. Topographic features of present-day shelves serve as a guide for fine-scale details. Information on topography, sediments, and discharge of water and sediment for a number of temporal and tropical continental shelves (e.g., U.S. Atlantic, Mediterranean and East China Sea) will allow for preliminary predictions of dissection patterns

Available data on the width, density, orientation, depth, and other characteristics of exposed and buried channels including sediment type that encases the channels are compared with the simulations in order to validate and calibrate the model. The nature of marine channel fill also provides insight into the regional effects of sediment supply, flow characteristics, wave-base erosion, and physiography. This comparison is designed to allow for model refinement, including calibration and adding features where appropriate (e.g. channel meandering, iceberg furrowing, planation and valley infilling during sea level rise, isostatic adjustment and tectonic forcing).

A global database provides for initial inputs and constraints for models. The database is indexed by margin type, geographical area, climate conditions, shelf characteristics, and channel morphology. The global atlas includes shelf gradient and width, sediment type and distribution, channel morphology and infill, drainage architecture, adjacent river systems, morphology of river systems, relative sea level curves for geographic areas, wave climate. The RiverTools® program (and other GIS software as needed) are used to perform a comprehensive analysis of real and simulated elevation grids. The measurements and information obtained from this analysis will be used to better understand the geometric and statistical characteristics of landforms and how these characteristics vary from one geologic setting to another. The physically based landform models of Howard (1994, 1996, 1997, 1999), Peckham (1998, 1999), and Smith et al. (1997a, 1997b) are used to classify "terrain types" in terms of the initial and boundary conditions (e.g. geology, erosion rates, excess rain rates) that produced the terrain types. The landform models are solved numerically for (a) different sets of input parameters (e.g. rate constants) and (b) different sets of initial and boundary conditions (e.g. fixed or changing base level). For a given set of input parameters, the model output (gridded terrain) display visual and statistical similarities that can be quantified and compared to field observations.

Numerical and Data Approach: Sediment Burial of Marine Landscape

Simple scaling relationships are developed for deposition rate as a function of sediment input rates from rivers (and coastal erosion), wave and current conditions, and shelf geometry. This provides a measure of expected burial depth for channels on the last lowstand surface. The bulk estimates used in this analysis are being refined with more detailed consideration of the nature of sediment delivery to the shelf (e.g., episodic storm-driven flooding vs. seasonal snowmelt flooding; the role of estuaries) and sediment redistribution, bypassing and deposition on the shelf (e.g., the long-term manifestation of short-term, episodic, storm-driven transport on the shelf). Process-based models provide for considerations of the nature of sediment delivery to the shelf and sediment redistribution, bypassing and deposition on the shelf. *Hydrotrend* (Syvitski et al., 1998; Syvitski and Morehead, 1999) is used to provide realistic estimates of the time varying nature of sediment flux from rivers, both under modern conditions and under paleo conditions. *2D-SedFlux* (Syvitski et al., 1999; Syvitski and Hutton, 2001) is used investigate shelf deposition under a variety of scenarios (changing river sediment input rates and timing, wave and current characteristics, sediment properties).

Nearshore processes must be accounted for in models of the morphologic evolution of the continental shelf. Modeling of seascape evolution during rise or fall of sea level requires some means of accounting for the changes in texture and morphology that occur as the nearshore zone moves through a region of the shelf. This problem is initially addressed by using a simple reworking function based on wave conditions. Comparison of model results with stratigraphic field data suggests that simple characterization work to a first order.

Transport and deposition on the continental shelf depend on wave and current conditions. Both waves and currents are functions of atmospheric conditions (primarily winds) and bathymetry. These have changed through the period of sea-level rise in the Holocene. Knowledge of these changes is necessary when modeling sediment deposition and morphologic evolution of the continental shelf during the Holocene. Wind patterns from atmospheric paleoclimate models and the resulting coastal circulation patterns from ocean hydrodynamic models would be compared to modern conditions.

Summary

A database and numerical approach is designed to quantify the development of incised channels located on continental margins during periods of sea level fall. Similarly a database and numerical approach is designed to quantify the degree of burial, and the character of burial material. Initial results are very encouraging.

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H 517158 (11)

Geological and Geophysical Reconnaissance for the ONR Geoclutter Program

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Long-term goals

The common goals are to: 1) understand the acoustic scattering process in shallow water, with the objective of designing physics-based signal processing algorithms to distinguish naturally-occurring features (e.g., iceberg scours, shallow gas accumulations, outcrops of high-amplitude shallow subsurface reflectors, shallowly-buried meandering channels) which are ubiquitous on the world's continental shelves, so-called "geoclutter", from man-made targets of similar dimensions (e.g., submarines), and 2) to predict the distribution and properties of geoclutter at a chosen U.S continental margin test site, with eventual application to other continental shelves of Navy interest globally.

Objectives

To plan and conduct an integrated, interdisciplinary, multi-year initiative, involving both geologists/geophysicists and acousticians, and including geologic and ocean acoustics/signal processing field and analysis components, in order: 1) to understand, characterize, and predict lateral and vertical, naturally-occurring heterogeneities (geoclutter) both at the seafloor and in the shallow sub-bottom of a U S continental margin test region, and 2) to identify, understand, characterize, and mitigate the geoclutter, specifically the heterogeneities that may produce discrete acoustic returns at low grazing angles, by carrying out precise acoustic reverberation experiments in the same region, so that such false alarms, or detects, of tactical sonar systems can be put in a proper context.

Approach

The underlying premise for geoclutter research is that both seafloor and shallow sub-seafloor geologic elements contribute to acoustic reverberation in shelfal water depths, in such a way as to affect tactical ASW sonar systems adversely. A comprehensive suite of reverberation measurements on a continental shelf, chosen because that shelf is also extremely well-characterized geologically, should result in improved characterization of the linkages between "clutter" and the ambient geologic environment. As part of ONR's recently completed STRATAFORM (Stratal Formation on Margins) Initiative, a "natural laboratory" to study source-to-sink sediment dispersal and preservation was established on the mid- and outer continental shelf off New Jersey Throughout this region, seismic interpretation and mapping and limited sampling have been combined with digital compilations of multibeam bathymetry and seafloor backscatter. As a result, this shelf has been chosen as the test site for both geoclutter acoustic reconnaissance (Phase I) and detailed geological and geophysical reconnaissance in support of Phase I (Phase II) The

key individuals involved at UTIG, other than the Principal Investigators listed above, include one post-doctoral appointee (Gulick) and one Ph.D student (Nordfjord) All will be part of Phase II data analysis and interpretation. Collaborations exist with the acousticians in the Geoclutter initiative through Dr. N. Makris, MIT, he is in charge of Phase I and follow-up interpretations. Other Phase II collaborators include Drs. L. Mayer, UNH, C. Sommerfield, UDEL, and S. Schock, FAU.

Work completed

Field experiments in support of both phases have now been completed. As a result of Geoclutter Phase I, conducted in April-May 2001, preliminary maps of prospective geoclutter targets were supplied to UTIG investigators for two primary areas (Figure 1) The detailed geophysical characterization of those areas, Geoclutter Phase II, has just been completed, in two parts. Part 1 was a cruise by the *Cape Henlopen*, CH01-17 (July 31-August 6, 2001), during which UTIG, UNH, and UDEL investigators collected suites of shallow subsurface compressional wave velocity measurements, grab samples, and short cores. Part 2 was a cruise by the *Endeavor*, EN359 (August 12-September 10, 2001), during which UTIG and FAU investigators used a deep-towed chirp sonar supplied by FAU to image the upper ~30 m of the geologic section, at frequencies of 1-4 kHz and at profile separations ranging from 0.5 nmi to ~50 m (Figure 1) Secondary acquisition using a hull-mounted Edgetech chirp sonar system was also conducted in Area 2.

Results

Hardware/software capabilities put aboard *Endeavor* by UTIG allowed chirp sonar data and precision navigation to be merged during EN359 Preliminary mapping of dendritic drainage patterns (Figure 2) and outcrops of important reflectors (i e., "R") was carried out aboard ship. These maps both confirm and amplify geophysical interpretations of high-resolution MCS and Huntec profiles made during STRATAFORM Some of these features appear to correlate spatially with Phase I geoclutter targets. However, more precise correlations between geophysical (i.e , chirp-sonar) characterizations of geology and prospecive geoclutter targets will await further Phase I and Phase II data analysis

Impact/applications

The maps completed during Phase II/EN359 data acquisition (Figure 2) will be refined and transmitted to Phase I investigators in various forms before the end of FY2002, so that prospective Phase I geoclutter targets identified in Areas 1 and 2 (Figure 1) can be tied to detailed geophysical characterizations of important geologic features. Over the next ~5 years, the Geoclutter initiative will 1) understand, characterize, and predict lateral and vertical, naturally-occurring heterogeneities both at the seafloor and in the shallow sub-bottom of the mid- and outer continental shelf off New Jersey, and 2) identify, understand, characterize, and mitigate that geoclutter, specifically the heterogeneities that may produce discrete acoustic returns at low grazing angles, so that such false alarms, or detects, of tactical sonar systems can be put in a proper context.

Transitions

DURIP funding has been secured to equip the DOSECC GLAD800 lake-drilling system with active heave compensation. A test of that system will be conducted offshore the U S. east coast aboard the WHOI research vessel *Knorr* in November 2001, with ONR support. If that test is successful, present planning calls for the GLAD800, mounted on the *Knorr*, to conduct sampling operations off New Jersey in September 2002. The goal of coring and sampling will be to confirm the geologic identity of Phase II geophysical reconnaissance.

Related projects

STRATAFORM and ODP (an international program funded through NSF) have both played prominent roles in ongoing New Jersey research over the past decade STRATAFORM/Geoclutter sampling envisioned for 2001 (and beyond) should proceed in tandem with additional acoustic reconnaissance, including perhaps additional 2D and 3D chirp sonar imaging, as part of Geoclutter.

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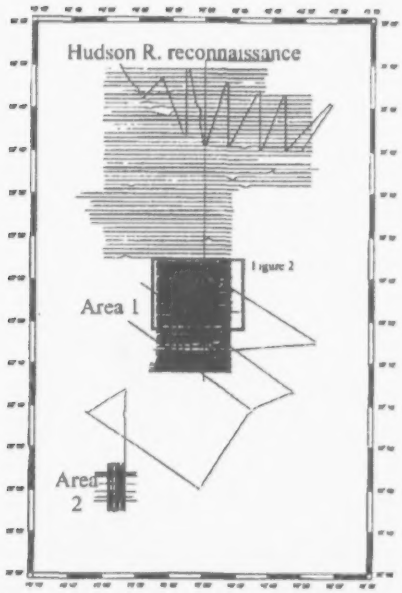

Figure 1: Deep-towed chirp sonar coverage, Endeavor cruise #359, August 12-September 10, 2001.

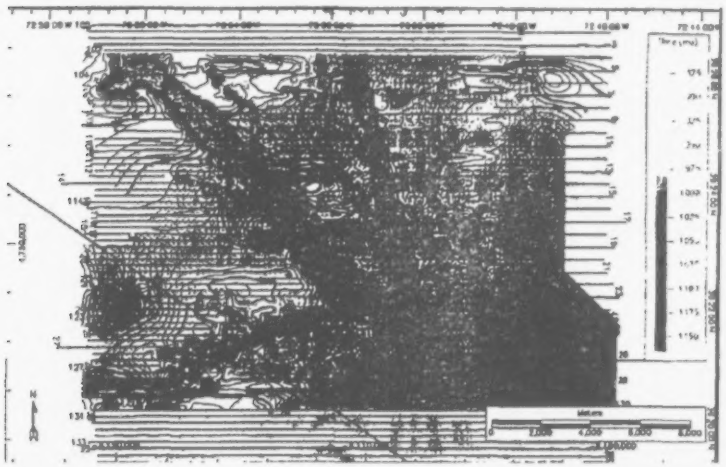

Figure 2: Dendritic drainage mapped in shallow subsurface, northern part of Area 1.

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#517159 (12)

The Wide Band Sonar: An experimental tool for measuring low frequency scattering in littoral waters

by
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Abstract -Defence Research Establishment Atlantic has developed a wide-band sonar (WBS) for collecting acoustic data in the open ocean The system employs a parametric array transmitter which enables direct measurement of seabed parameters in shallow water. To complement the parametric transmitter, a pair of 6-channel receivers have been developed for the system; a 6-channel superdirective line array is used as the principle receiver and a tri-axial intensity array is used to localize the platform and measure ambient noise directionality In this paper the attributes of the WBS will be outlined, the typical experimental geometries will be described, and a sample of the measurements made with the system during the Boundary 2001 trial will be presented.

I. Introduction

Defence Research Establishment Atlantic has developed a wide-band sonar (WBS) for collecting environmental acoustic data in the open ocean [1]. The sonar's direction is remotely controlled from a research ship via an RF radio link fixed to the system's surface float. This minimizes the risk of acoustic interference from the ship and prevents ship motion from compromising array stability. In addition to acoustic sensors, the array is instrumented with a range of non-acoustic sensors to assist in the evaluation of the data. The non-acoustic sensors include depth, tilt, roll, and heading sensors to monitor array position and direction, as well as accelerometers to monitor platform vibration The sonar head can be panned through 360° azimuth. The array can be configured to be either bottom-tethered (Fig. 1a) or bottom-mounted (Fig. 1b). In bottom-tethered mode the sonar support arm rotates 180° vertically so that the sonar can be positioned above or below the space frame. This enables measurements through 4π steradians. Platform stability is achieved by de-coupling the space frame from the surface float through a weighted cable and streaming the space frame into the prevailing shear current. In bottom-mounted mode a remote command is sent from the ship to the surface float to flood the sub-surface floats on the space frame to set the system on the seabed. This offers an extremely stable platform that permits coherent averaging of multiple pings. This is used in low SNR conditions such as measurements of backscattering strength at very shallow grazing angles; however, physical constraints limit the vertical range of angles to -30° from the horizontal up to+90°. Prior to recovery compressed air is forced into the sub-surface floats to evacuate the water.

The acoustic sensor suite consists of a parametric array transmitter (PATS), a superdirective endfire line array receiver (SIREM), and a tri-axial intensity array receiver (SIRA). The parametric array offers three advantages: First and foremost, due to the

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nature of signal generation in the parametric array, no sidelobes are formed. This feature avoids the added complexities of boundary interactions when making measurements in shallow water. Second, one can obtain a wider bandwidth than that obtained using a conventional source. In the present case a usable bandwidth of 1 kHz to 10 kHz is realized from a single transducer. Third, the beamwidth of the parametric array is only 3° thereby allowing measurements of backscatter as a function of azimuth as well as out of plane bistatic scatter. The principle receiver for measuring acoustic backscatter is the SIREM line array mounted on the PATS head. The array yields gains of up to 15 dB across the sonar's frequency band from an array aperture only 0.8 m long. The SIRA intensity array is a secondary receiver and is used to measure ambient noise directionality. The superdirective array weights can then be optimized for the specific ambient noise field. SIRA is also used to localize the platform during bistatic experiments. It's bearing accuracy is better than ±0.5°. Following the introduction, a sample of the measurements made with each of these systems during Boundary 2001 will be presented. Space constraints will limit discussion of the results significantly.

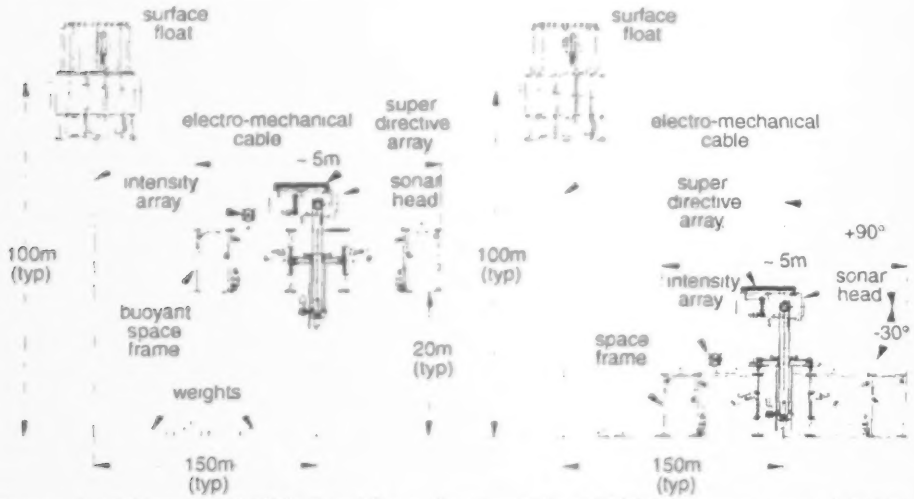

Figure 1: Schematic of Wide Band Sonar bottom-tethered (left), bottom-mounted (right). Note that the pivot point for the sonar support arm is different for the two configurations.

II. The measurements

Figure 2 compares the beam pattern for a 4 kHz difference frequency made at DREA's calibration barge with one taken at sea during Boundary 2001 when the WBS was bottom mounted. This figure serves to show a typical beam width as well as the stability of the platform during the sea experiment to allow such a measurement. The source level at 4 kHz is 183 dB//1 $\mu Pa^2/Hz$@1m. Figure 3 compares the measured gain against ambient noise for a 3rd order superdirective array with modeled results. The model assumes a 3-dimensionally isotropic ambient noise field and a system noise floor 30 dB below

ambient. The system is designed as a 5th order superdirective array which would provide an additional 5 dB increase in gain against ambient noise; however, a phase mismatch between the two National Instruments data acquisition boards prevented this during the experiment. The error has since been corrected.

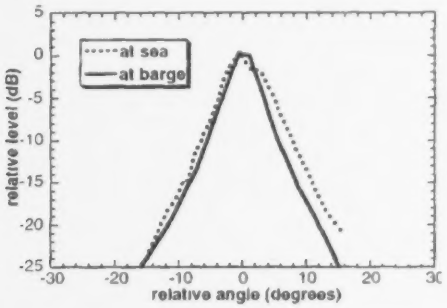

Figure 2: Comparison of beam calibration results collected at sea with those taken at DREA's acoustic calibration barge. The data is for a difference frequency of 4 kHz.

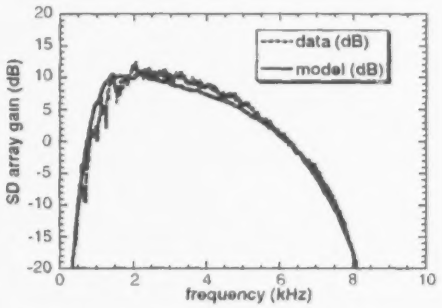

Figure 3: Model-data comparison of gain against a 3-dimensionally isotropic ambient noise field using a 3rd order superdirective array.

A sample of the bearing estimation obtained by SIRA is shown in Figure 4. A series of fifty 4 kHz pulses, 0.5 ms in duration were projected from a source located 160 m away on the UAT vertical line array. The vector intensity is displayed as vertical and horizontal slices to ease interpretation. The solid line is the average of the 50 pings and the length of the line gives the magnitude of the intensity. The points along the line are the individual pings. The close packing of the points reflects the stability of the WBS and UAT during the bistatic experiment.

Figure 5 contains an energy time series from a bottom backscattering experiment performed at 4 kHz and 8 kHz with the transmit array directed at 3.5° and 10° grazing. The initial returns from the seabed are circled. The displacement of the 4 and 8 kHz peaks from one another in the 3.5° data corresponds to a ±0.1° uncertainty in angle, this is within the mechanical tolerances of the array.

III. Concluding remarks

The Wide Band Sonar is an effective tool for interrogating the seabed. It permits a wide range of experimental geometries, minimizes the risk of acoustic interference from the ship and prevents ship motion from compromising array stability. Measurements made during the Boundary 2001 trial include low-grazing angle backscatter, bistatic scatter, and ambient noise directionality.

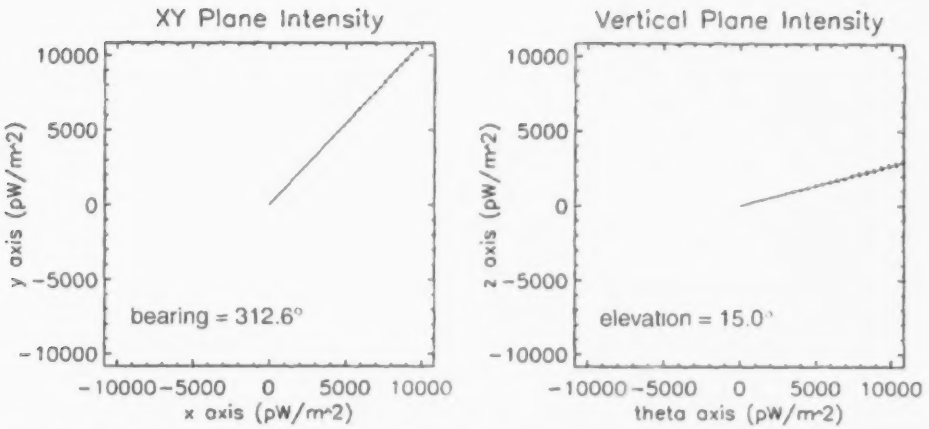

Figure 4: Sample plot of the horizontal (left) and vertical (right) slices of the intensity vector collected using SIRA during a localization experiment

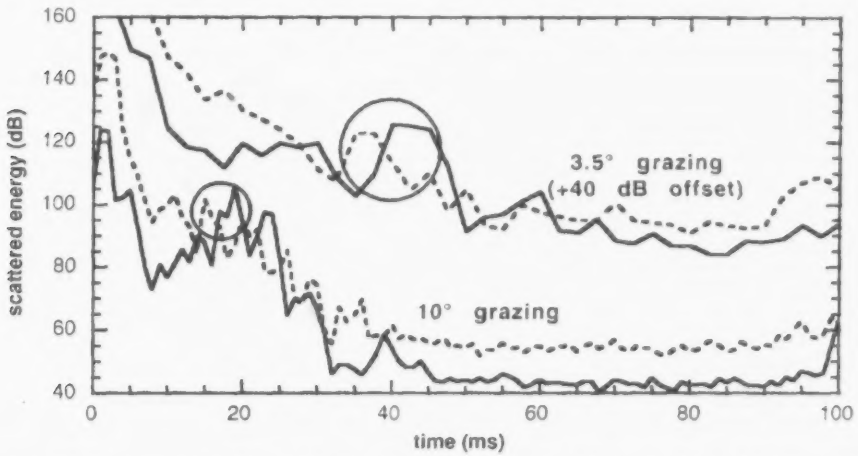

Figure 5: Time series of bottom backscattered returns at 4 kHz (dash) and 8 kHz (solid), for grazing angles of 10° and 3.5°. Initial returns from the seabed are circled.

IV. References

1 Paul C. Hines, W. Cary Risley, and Martin P. O'Connor, "A Wide-Band Sonar for Underwater Acoustics Measurements in Shallow Water," Proceedings: Oceans'98, Nice, France, Sept. 29-Nov. 1, 1998.

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#517160 (13)

Direct path measurements of bistatic and monostatic scattering in littoral waters in the 2-8 kHz Frequency Band

by

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Direct measurements of acoustic scattering from the seabed at shallow grazing angles presents a considerable challenge in shallow water. Specifically, returns from the air-water interface typically contaminate the signal of interest. To address this issue DREA has developed a pair of sea going research systems for measuring acoustic scatter from the seabed in shallow water environs In this paper the acoustic attributes of both systems will be outlined, the experimental geometry will be described and measurements of acoustic backscatter and forward scatter collected during one such experiment will be presented.

I. Introduction

Defence Research Establishment Atlantic has developed a wide-band sonar (WBS) for collecting environmental acoustic data in the open ocean. This system is highlighted in a companion paper in this Proceedings as well as in [1] The Underwater Acoustic Target (UAT) is a ship-launched echo-repeater with a 15 hydrophone vertical line array (VLA) and a non-acoustic section (NAS) suspended beneath the projectors. Up to 8 hydrophones can be recorded simultaneously but must be selected prior to deployment. with echo-repeat mode disabled, it functions as a remotely controlled source and receiver The UAT can be deployed free-drifting or bottom-tethered Data can be recorded by the UAT directly or can be telemetered back to the tending ship. These systems were situated within 150 m to 300 m of one another and bistatic and monostatic scatter from the seabed were measured at locations on Scotian Shelf and Strataform. Figure 1 shows a schematic of the UAT bottom-tethered and the WBS bottom-mounted as used during these experiments. Following the introduction, the experimental geometry will be described and a sample of the forward and backscatter measurements made with these systems during Boundary 2001 will be presented. Space constraints will limit discussion of the results significantly

II. The deployment

The experimental geometry was a critical factor in this experiment. If the two systems were too close (<100 m) the spatial resolution of the VLA would be too coarse ; it they were to far separated (>300 m) the VLA would span too narrow a vertical beam of angles Noting that both systems weigh over 2000 kg, this was not a trivial concern The UAT was launched first and an initial localization was performed using DREA's FITDS system [2]. The ship would then steam upwind and drift back past the UAT location crossing within about 100 m of the UAT way-point. During this trial run, the ship's drift

vector would be monitored. The space frame was readied on the ship's crane and the launch run would commence A delay of approximately a 4 minutes occurred from the time the spaceframe was lifted off the deck to the time it was released into the water. This delay was accounted for during the deployment so that the spaceframe was released at CPA. Immediately after releasing the spaceframe, the weighted cable was rapidly winched into the water to avoid towing the system. Once the cable was deployed the surface float was connected and deployed Once deployed the WBS was localized with FITDS [2] The experiment was performed at two sites with the systems separated by 272 m at Strataform and 164 m at Scotian Shelf.

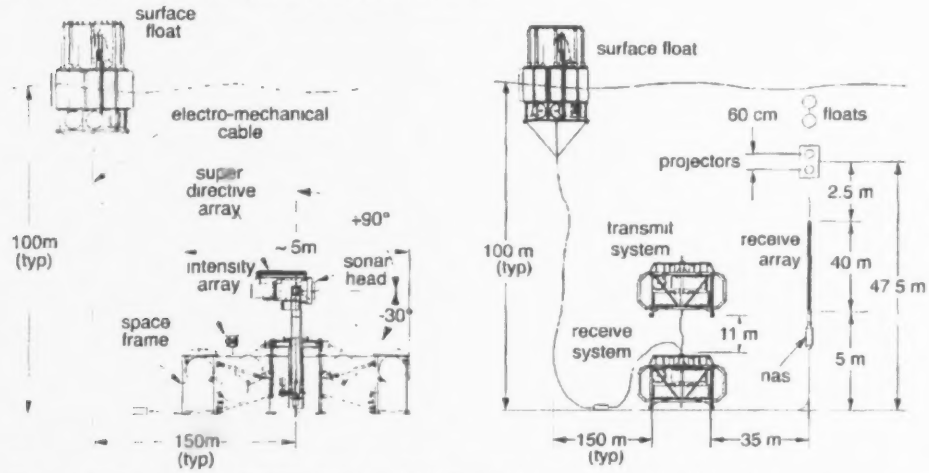

Figure 1. Schematic of WBS (left) and UAT (right) configured for bistatic experiments.

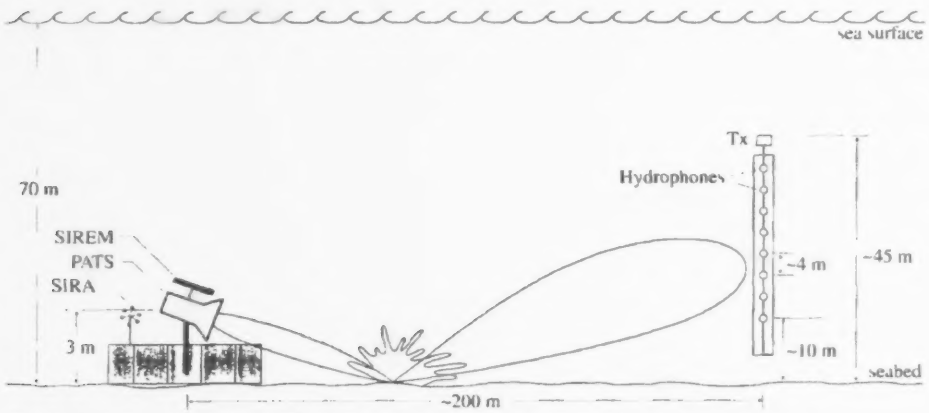

Figure 2. Cross-section schematic of typical geometry for bistatic experiments

III. The experiment

Figure 2 contains a schematic of the bistatic experimental geometry. The WBS was pointed at a grazing angle such that the specular reflection insonified at or near the center of the VLA at an azimuth of -15° relative to the vertical axis of the UAT array This corresponded to 9° grazing at Scotian shelf and 5°grazing at Strataform): A series of 50 pulses were transmitted by the WBS at 2, 4 and 8 kHz with a pulse repetition frequency (PRF) of 4 per second. Forward bistatic scatter was recorded on the UAT and backscatter was recorded on the WBS superdirective array. The parametric array transmitter was rotated 2° in azimuth and the sequence was repeated. This was done from -15° to +15° relative azimuth This experiment resulted in measurements of vertical and horizontal scattering from specular as well as backscatter as a function of azimuth. At various times throughout the experiment, the SIRA intensity array was switched in and the UAT transmitted sets of fifty of 4 kHz tone bursts, 0 5 ms in duration. These pulses were processed to localize the UAT [3] as well as to quantify any motion of the UAT The experiment was repeated for grazing angles approximately ± 3° from specular as measured relative to the midpoint of the VLA.

IV. The measurements

The waterfall display in Figure 3 shows the received energy for all 8 hydrophones as a function of azimuth and grazing angle at 4 kHz. The error bars on the data represent 2 standard deviations about the mean levels shown. The specular reflection occurs at approximately 10°, midway between curves 4 and 5 For reference, the ambient noise level is drawn relative to the lower most solid curve Figure 4 compares the beam pattern of the parametric transmitter measured at sea, to the energy received on a single hydrophone. Spreading of the energy is evidenced by the broadening of the beam relative to the beam pattern. The energy curve flattens off about 14 dB down from the peak due to background noise attributed to the WBS platform.

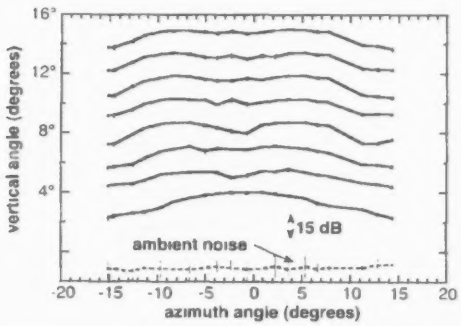

Figure 3: Waterfall display of bistatic scatter measured at Scotian Shelf (4 kHz).

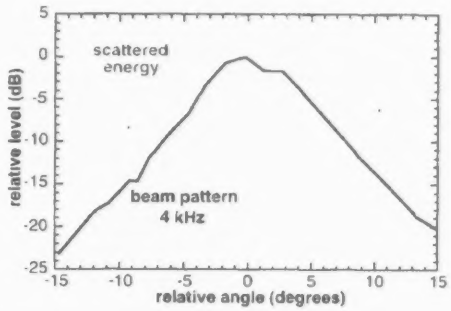

Figure 4. Measured beam pattern compared to bistatic scattered energy.

This experimental geometry provided an opportunity to collect backscatter data as a function of azimuthal angle on the WBS during the bistatic scattering experiment. (It also enabled spatially coincident measurements of forward bottom loss/scatter and backscatter as a function of grazing angle. Analysis of these data have only just begun, preliminary results are contained in Figures 5 and 6. Figure 5 shows the azimuthal dependence of the backscattered energy at 4 kHz that was collected on the WBS while the bistatic data shown in Figure 4 was being collect by the UAT. Figure 6 shows the backscattered energy as a function of grazing angle at 2, 4, and 8 kHz. The three curves in Figure 6 are corrected for the frequency dependence of the source level but not for the grazing angle dependence of the spreading loss.

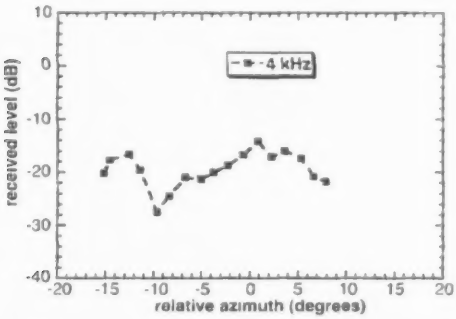

Figure 5 Azimuthal dependence of the backscattered energy.

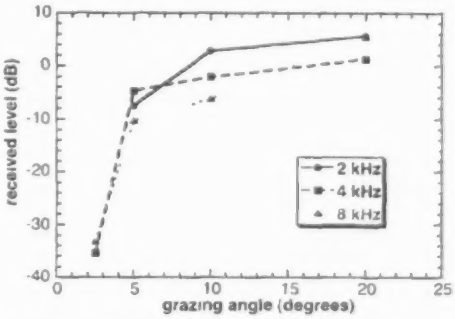

Figure 6: Backscattered energy as a function of grazing angle

V. Concluding remarks

The WBS and UAT were used to gather a unique data set of out of plane bistatic scatter and backscatter as a function of azimuth in the 2-8 kHz range. The experimental geometry also enabled spatially coincident measurements of forward scatter and backscatter – samples of which are contained herein.

VI. References

1 Paul C. Hines, W. Cary Risley, and Martin P O'Connor, "A Wide-Band Sonar for Underwater Acoustics Measurements in Shallow Water," Proceedings: Oceans'98, Nice, France, Sept. 29-Nov. 1, 1998.

2 Osler, J and Beer, J., "Real-time Localization of Multiple Acoustic Transponders Using a Towed Interrogation Transducer", Proceedings of Oceans 2000 MTS/IEEE Conference, Vol 1, 2000, 8 pp 725-732

3 Localization using SIRA provides a more accurate bearing angle than FITDS and can be done without maneuvering the research ship

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Seabed and Sub-bottom Classification Using Measurements of Normal Incidence Backscatter Measurements in the 1-10 kHz Frequency Band

by

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Abstract - It has been established that the first and second normal incidence acoustic returns from the seabed can be used as a classification tool to discriminate between, for example, sand, mud, or rock bottoms. Typically this is accomplished using mono-static echo sounder systems that operate in the range of several 10s of kHz so that bottom roughness at the seabed interface is the dominant scattering mechanism. Theoretical results indicate that at lower frequencies, returns from the sub-bottom should provide an additional discrimination tool without significantly corrupting the seabed information contained in the interface scatter returns. This paper presents an experimental methodology for making these normal incidence measurements made in the 1 to 10 kHz frequency band using a moored vertical line array of receivers and pair of projectors. The projectors have been used in tandem to create aliased cardiods that significantly reduce interference due to the sea surface reflection. The conventional classification technique relies upon treating the first bottom echo as a mono-static arrival and the second bottom echo as a bi-static arrival. The use of a vertical line array also allows a similar comparison to be made between hydrophones proximal to the source (mono-static) and hydrophones that are farther away (bi-static). Experimental results from the ONR Strataform area are presented.

I. Introduction

A surficial sediment classification technique using the first and second normal incidence acoustic seabed returns, typically from mono-static echo sounder systems that operate in the range of several 10s of kHz, has been developed by Heald and Pace [1]. At these frequencies, bottom roughness at the seabed interface is the dominant scattering mechanism. The first seabed return (Fig. 1) is treated as a far-field, mono-static, arrival whose intensity is inversely proportional to the mean square slope—a roughness parameter [2]. The second seabed return is treated as a near-field bi-static arrival, with a virtual source above the water surface (Fig. 1), whose intensity is proportional to the Rayleigh reflection coefficient. The intensity of the first and second seabed returns are integrated over time to yield energy, E_1 and E_2 respectively. (For E_1, the integration is performed over only the tail of the return to avoid overload of the receive amplifier whereas E_2 is integrated over the complete backscatter return). The ratio E_1/E_2 is used to classify different sediment types [1]. The technique is based on a Helmholtz-Kirchhoff model with gaussian roughness and ignores any coherent reflections and seabed penetration.

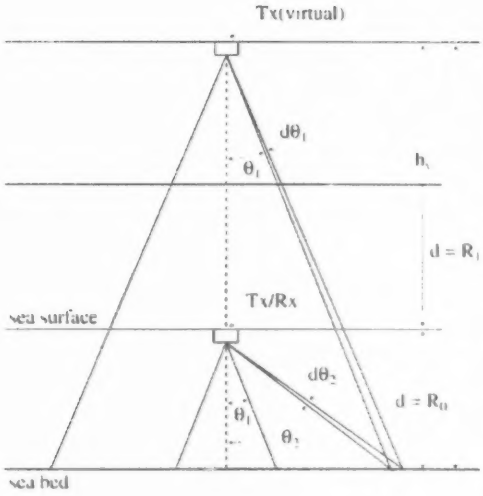

Figure 1: Schematic of the equivalent geometry with virtual source for the 2nd seabed return from the seabed interface located above the sea surface

Hines and Heald [3] have extended this technique to lower frequency (1 to 10 kHz range) by including volume scatter from coherent energy penetrating into the seabed. In this frequency range, scatter from the interface initially dominates the intensity of the arrivals. However, because of its rapid decay, the intensity is subsequently dominated by volume scatter that decays more gradually. The transition between surface and volume scatter, and their respective rates of decay, form the basis of the sub-seabed classification technique. The intensity time series are a function of roughness parameters, frequency, and the composition of the surficial sediment layer. Wide bandwidth, or multi-frequency systems, may exploit the frequency dependence and provide further discrimination regarding seabed composition.

An example of the Hines and Heald [3] intensity versus time model predictions for the first seabed arrival are presented in Figure 2 for a 5 ms pulse vertically incident on a sand seabed. The surface scatter intensity, I_{sb1}, is calculated for three values of surface roughness and a fixed correlation length of 1.5 m. The volume scatter intensity, I_{vb1}, is calculated using the roughness parameters specified in [3] and the remaining physical parameters are from [4]. The predicted intensity of the volume and surface scatter are superimposed on the same plot in Figure 2. The intensity curves start at 5 ms, that is the time when the pulse that is incident on the seabed transitions to an annulus from a spot. This time is also when the peak in I_{sb1} and I_{vb1} is expected to occur. The decay of I_{sb1} is a function of seabed roughness. The decay and initial level of

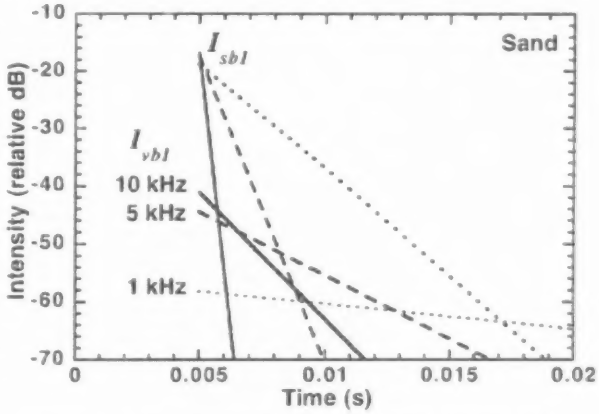

Figure 2: Comparison of I_{sb1} for a sand bottom with rms roughness of 3.75 cm (solid black line), 7.5 cm (dashed red line), and 15 cm (dotted blue line) and I_{vb1} at frequencies of 1, 5, and 10 kHz

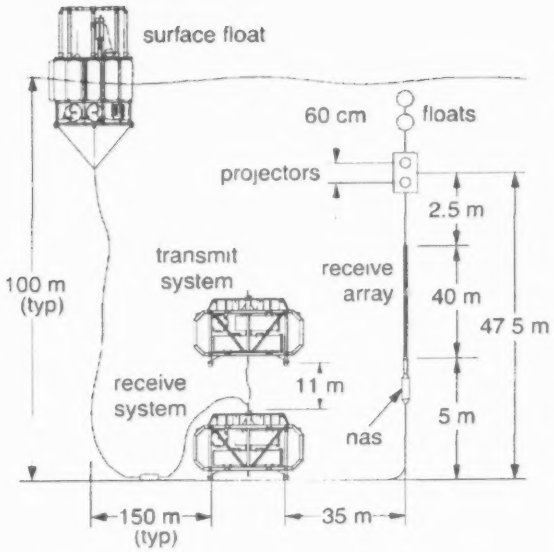

Figure 3. Schematic diagram of the DREA Underwater Acoustic Target deployment.

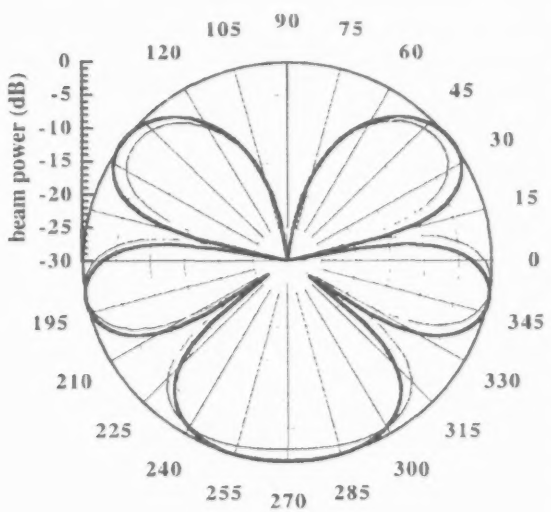

Figure 4 Theoretical (solid black line) and measured (closely spaced red dots) beam patterns for the steady state radiation from a pair of transducers separated by $5\lambda/4$ and driven in phase quadrature. The null is directed at the sea surface.

I_{sbl} is a function of frequency and sediment type.

II. Experimental Methodology

Experiments were conducted using the Defence Research Establishment Atlantic (DREA) Underwater Acoustic Target (UAT). The UAT is a ship-launched echo-repeater with a 15 hydrophone vertical line array (VLA) and a non-acoustic section (NAS) suspended beneath the VLA (Fig. 3) Up to 8 hydrophones can be recorded simultaneously, but must be selected prior to deployment. For the seabed classification experiments, the hydrophones were selected to be equally spaced, to include the hydrophone closest to the projectors, and to provide the maximum possible aperture. Immediately above the VLA, there is a pair of ITC 1007B 16 cm diameter spherical projectors whose acoustic centers are separated by 62.5 cm The projectors are controlled individually but may be used in tandem with user specified time and phase delays. With echo-repeat mode disabled, the UAT functions as a remotely controlled source and receiver Although the UAT can be used in a free-floating mode, it was bottom tethered for this application. The power and electronics modules for the UAT are housed in two space frames, for the transmit and receive systems respectively. These space frames were displaced as far as possible horizontally from the VLA to

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minimize their influence on the scattering measurements. Data can be recorded internally by the UAT or telemetered by radio link to the tending ship–the latter being the preferred and typical mode of operation.

For these seabed classification experiments, acoustic energy that propagates from the source and is reflected by the sea surface gives rise to a series of arrivals that are unwanted and can mask the seabed reflected arrivals that are of interest. The amplitude–and hence the importance–of these arrivals can be reduced by using a directional source with the main lobe pointed at the seabed. This was achieved by time delaying and phase inverting the output from the upper projector such that cancellation occurs above the transducers and reinforcement occurs below (Fig. 4). The time delay was equal to the time of flight between the transducers, with the upper projector delayed relative to the lower. Frequencies were selected such that the transducers were separated by $5\lambda/4$, $9\lambda/4$, and $13\lambda/4$ (approximately 3 kHz, 5.3 kHz, and 7.7 kHz respectively).

III. Results

The median intensity of two hundred 1 ms duration pings at 5333 Hz measured on four hydrophones in the vertical array is displayed in Figure 5. There are numerous arrivals in each time series including the direct arrival, 'D', and arrivals with a number of sea surface, 'S', and/or seabed, 'B', reflections.

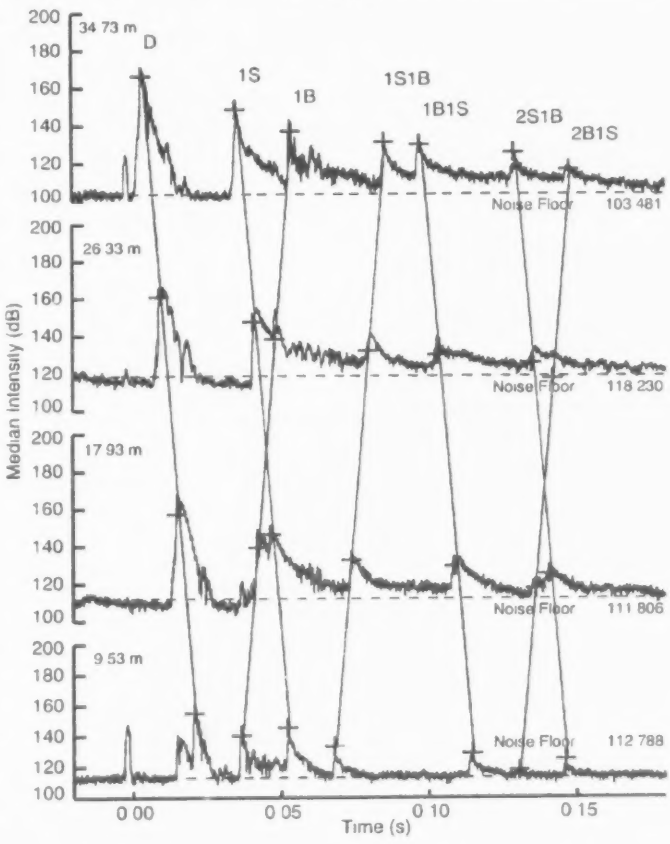

Figure 5: Time series of median intensity on four equally spaced hydrophones during a seabed classification experiment. Green crosses represent theoretical arrival times and amplitudes. Diagonal lines denote the initial direction of propagation, downward (blue) or upward (red). Inset numbers are height of the hydrophone above the seabed.

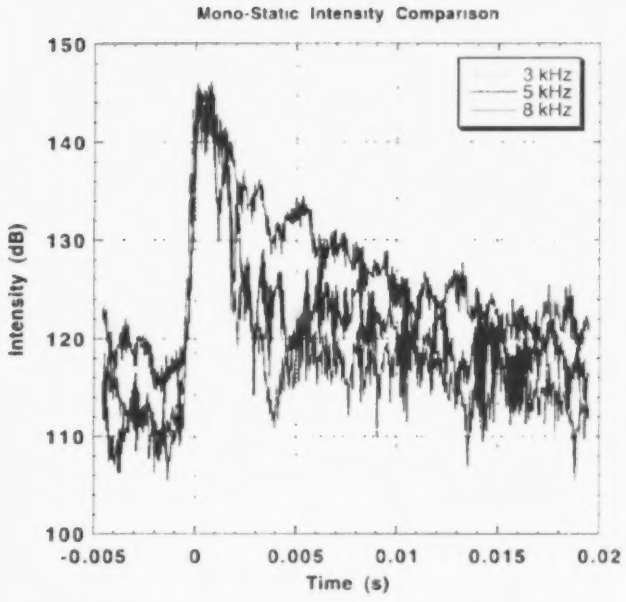

Figure 6: Time series of median intensity of the 1B arrival on the uppermost hydrophone at three frequencies for a 1 ms duration pulse

The theoretical arrival times (green crosses in Fig. 5) use a depth averaged sound speed of 1465 m/s and assume that the VLA is perfectly vertical. The amplitude calculations employ the drive voltage and transmitting voltage response curves for the projectors to determine the source level, assume a spreading loss of $20\log(r)$, where r is the length of the propagation path, a reflection loss of 0 dB at the sea surface and 10 dB for each seabed reflection. Although there are some calibrations issues to be resolved (as evidenced by the amplitude mismatch of the direct arrivals), the amplitude discrepancy between the 1S theoretical value and the median intensity is due to the effectiveness of the phase quadrature beam pattern in eliminating radiation to the sea surface and any scattering that may have happened. (Winds were 20 knots during the experiment and both the wind and seas had been building during the previous eight hours).

The decay of the 1B arrivals on the uppermost hydrophone at three frequencies is displayed in Figure 6. The shapes of these curves are consistent with the theoretical predictions for a sand dominated seabed (Fig. 2). Although the decay curves have a considerable amount of structure, perhaps due to some layering in the seabed, their slopes and relative levels are as predicted. The initial decay is most rapid at the lowest frequency followed by a rapid transition to a slowly decaying volume scattering regime. At the two higher frequencies, the intensity levels at the onset of volume scattering are progressively higher and decay more rapidly than the lowest frequency. These results were collected in the vicinity of the AMCOR 6010 on the ONR Strataform experimental area–a location where geoacoustic seabed properties have been measured by independent means and summarized in [5]. The seabed is described as having "near surface layering" with the first twenty five metres being a "sandy-silty-clay" layer. The average compressional sound speed in the first 5 m is 1560 m/s and reaches 1830 m/s at 30 m depth.

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While this paper has focused on the first seabed reflection, 1B, received on the hydrophone that is closest to the source location, there are two other arrivals that will be considered in subsequent research. These are the second seabed reflection, 2B1S, and a 1B arrival measured on the deepest hydrophone, as far away from the source as possible, in order to have the maximum bi-static angle. The former will allow a more direct comparison of the lower frequency model extension [3] with the original higher frequency classification technique [1]. The latter should provide an alternate means of obtaining the bi-static geometry, required by [1], using an arrival that has a higher signal to noise ratio than the 2B1S arrival (Fig. 8).

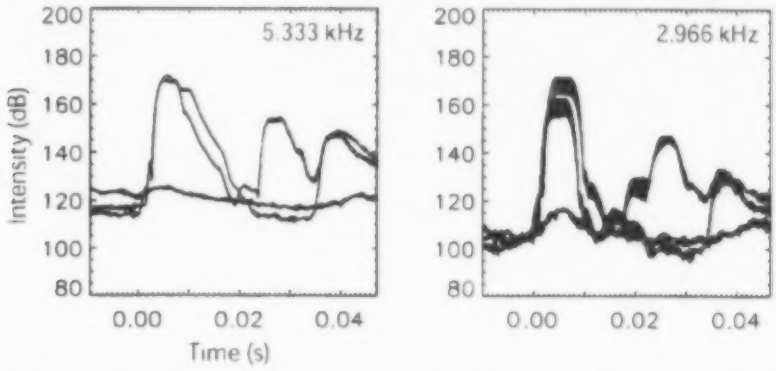

Figure 8: Time series of median intensity for a 5 ms pulse at two frequencies. Red line is the 1B arrival on the uppermost hydrophone, blue line is the 2B1S on the uppermost hydrophone, and the black line is the 1B arrival on the deepest hydrophone.

IV. Conclusions

An experimental geometry for testing model predictions for seabed and sub-seabed sediment classification has been developed and experiments have been conducted in open ocean conditions. Initial results from these experiments on a sand dominated seabed have a frequency dependence that is consistent with theoretical predictions. This suggests that a broadband normal incidence sonar system operating in the 1 to 10 kHz band may be used for purposes of seabed and sub-seabed sediment classification.

V. References

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Geoacoustic Characterization of Boundary 2001 Experimental Locations

by

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Abstract – DREA has collected geoacoustic data to characterize the experimental areas for the Boundary 2001 sea-trial, in particular Sable Island Bank on the Scotian Shelf. Measurements include bathymetry, vertical incidence seismic reflection, sidescan sonar, wide angle reflection and bottom loss (WARBLE), grab samples, and geotechnical data using a cone penetrometer. The Scotian Shelf has numerous surficial seabed features that could create false targets, or "geoclutter", for tactical and low frequency active sonars. It has also been observed that the seabed at experimental location NS-1 is dynamic, bed forms have rotated or been destroyed in a six month interval between sidescan measurements.

I. Introduction

The surficial sediment distribution of the Scotian Shelf (Fig. 1) is closely related to the processes that transpired during and since the last glaciation. In general, the shallow water bank areas tend to have sand or gravel overlying glacial till and then a consolidated rock layer (sedimentary offshore and metamorphic inshore). Meanwhile, the deep basins tend to have clays and silts that are washed away from the bank areas and deposited on top of the deeper till and rock layers. Osler [1] provides a summary of the geological history, geoacoustic properties of surficial sediments, and general oceanography. Table 1 includes a brief description of the different seismic units.

Table 1: Summary of Surficial Sediment Units

Name	Description	Seismic Character	Compressional Sound Speed (km/s)
Scotian Shelf Drift	Glacial Till	Incoherent seismic reflectors	1.75 to 1.92
Emerald Silt	Glaciomarine sediment	Continuous reflectors	1.48 to 1.59
Sable Island Sand and Gravel	Well sorted sand and gravel	Highly reflective	1.6 to 1.8 (sand) 1.8 to 1.9 (gravel)
LaHave Clay	Silty clay confined to basins	Seismically transparent	1.46 to 1.49 km/s
Sambro Sand	Silty sand grading to gravelly/well sorted sand.	Highly reflective	~1.65 km/s

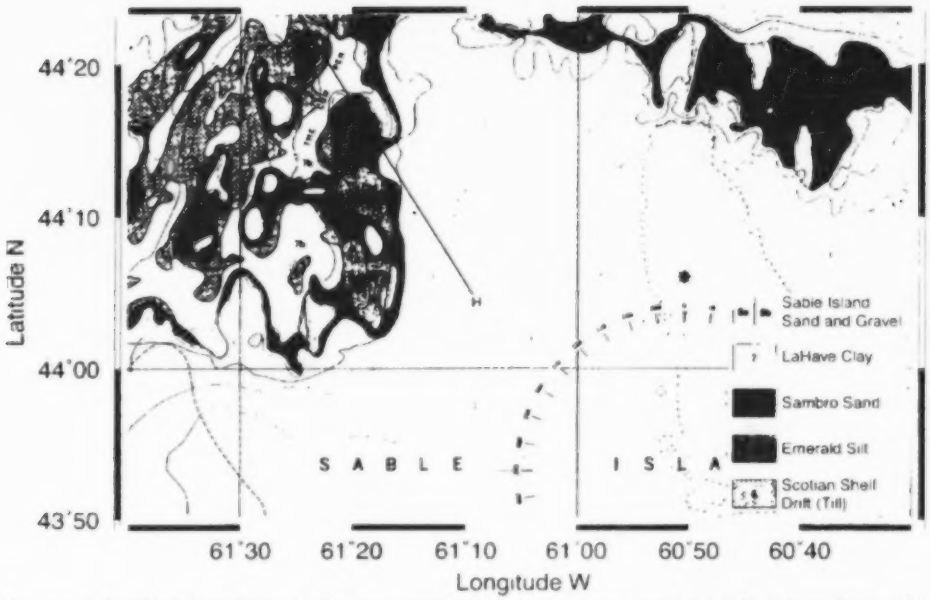

Figure 1: Surficial geology of the area surrounding experimental site NS-1 from King [2]

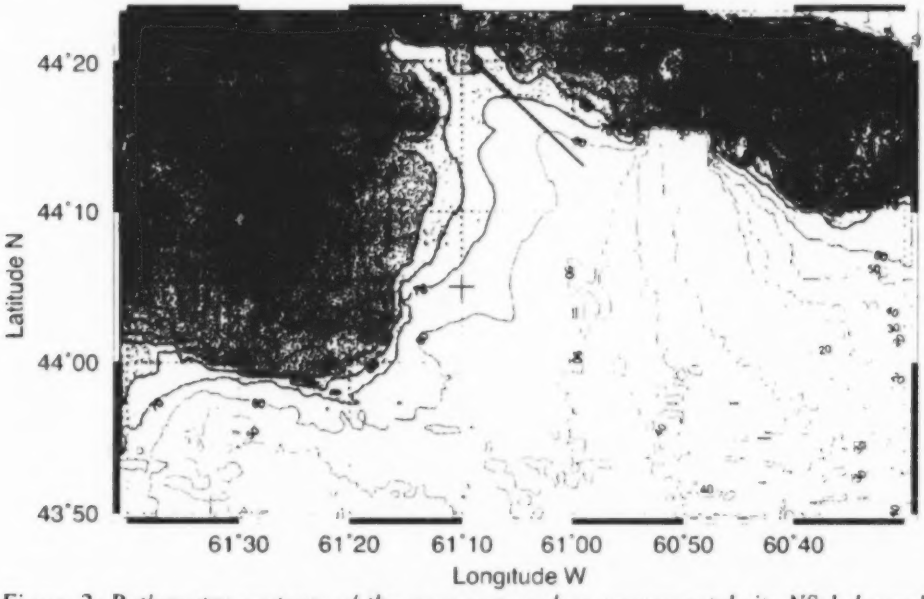

Figure 2: Bathymetry contours of the area surrounding experimental site NS-1 derived from the Canadian Hydrographic Service digital compilation. Approximate location of exposed portion of gas pipeline is in red

Surficial seabed features abound on the Scotian Shelf including: glacial till ridges, gas escape craters, or pock marks (usually in the basins), gravel berms, iceberg keel scours, buried channels, bedrock outcrops, sand waves and ridges, shell beds, and pipelines. Several criteria guided the selection of the experimental site. It is a considerable distance, approximately 45 n mi., from the shelf edge to avoid internal wave activity and strong sound speed gradients. It is also away from oil and gas production platforms (the nearest is Alma at 43°35.7N 60°40.9W) and the seismic exploration presently concentrated along the shelf edge to avoid interfering sources of noise. It has a predominately sand seabed with a diversity of other seabed types and features nearby. And, it has a water depth that is suitable for deploying DREA wide band sonar (WBS) and underwater acoustic target (UAT) research equipment (approximately 60 to 120 m).

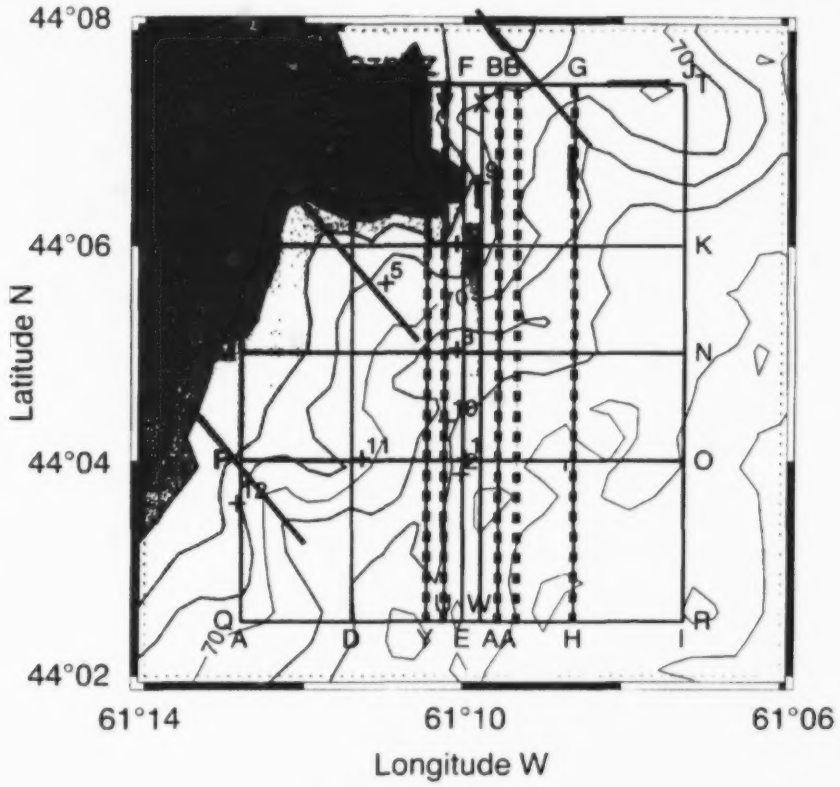

Figure 3. Summary of geophysical observations at NS-1. Bathymetry contours are from a compilation of single channel echo sounder measurements from CFAV Quest. Klein 5500 sidescan and EdgeTech X-star chirp sub-bottom profiler lines collected in October 2000 are marked by the black lines with red letters at end points. Tracks repeated in May 2001 are dashed green lines. Brown + symbols indicate the locations of grab samples and pink lines indicate the extent of a burial channel. Solid red lines mark sand ridge crests.

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II. Characterization of Surficial Geology

To characterize the surficial geology at NS-1 (44°05N, 61°10W), a series of sidescan and sub-bottom profiler survey lines were collected (Figure 3). Two interesting features were noted in the seismic reflection data, an infilled channel that is at least 5 to 10 m deep and approximately 400 m wide, situated in a swale to the north of NS-1; and an extensive series of depressions, approximately 1 m deep, that have more scatter and higher reflection loss than the surrounding seabed. Some of the depressions appear to be related, or rooted, to an irregular near surface reflector that tends to be from 0 to 3 m below the surface.

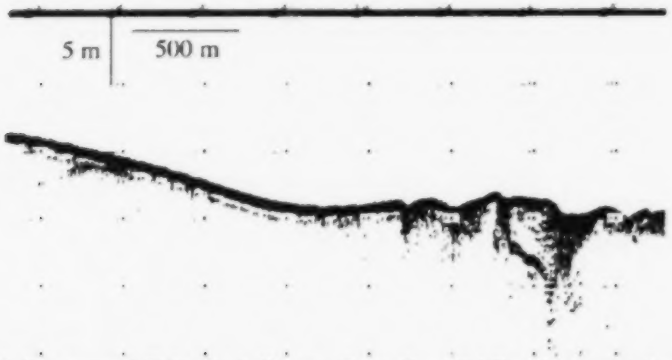

Figure 4. Hull mounted EdgeTech X-star, 5 ms 2 to 8 kHz chirp, sub-bottom profile along W-X. Note the filled channel on the right and the near surface reflector on the left.

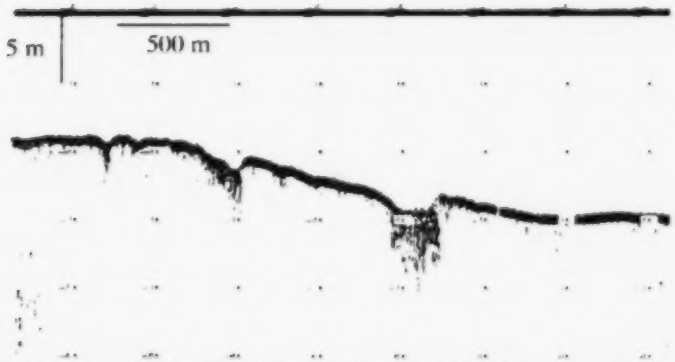

Figure 5: Hull mounted EdgeTech X-star, 5 ms 2 to 8 kHz chirp, sub-bottom profile along T-S Note the depressions with higher scatter and reflection loss and the near surface reflector on the left and right sides that may the base of the depressions.

The sidescan data (Fig 6) reveal an extensive series of quasi- parallel ribbons that are approximately 30 m apart and roughly parallel to bathymetry contours. They are likely parallel to the mean flow direction of the current, forming as the helical particle motion of the near seabed current deposits material in ribbons In October 2000, mega-ripples with wavelengths of 3 to 4 m and heights of ~0.2 m were superimposed on the ribbons (Fig 7a). The asymmetric shape of the mega-ripples is also indicative of a mean flow to the northeast. For the mean grain sizes in the areas where ripples are found (well sorted medium sand, 0.25 to 0.5 mm, ϕ=1.0 to 2.0), currents in the range of 0.4 to 0.6 m/s would have been required to create the mega-ripples On an Acoustic Doppler Current Profiler moored nearby from 15 to 25 October 2000, the largest near seabed currents were observed during the passage of Hurricane Michael on 19 October 2000. As the magnitude of these currents is in the required range for bed form development, and the sidescan data were collected days following the Hurricane, it is speculated that the mega-ripples were formed by the Hurricane and have since decayed (Fig 7b) The ribbons seem to be a more persistent feature as they were observed in archival data in 1982 (*C.S.S. Hudson* cruise 82-040) and during the repeat survey in May 2001 (Fig. 7b).

The sidescan data (Fig. 6) also reveal higher reflectivity patches that are quasi-orthogonal to the ribbons in the southern part of the survey area and more randomnly oriented in the north These patches are the depressed areas observed in the sub-bottom profiles (Fig 5) They contain material with a larger grain size (medium to very coarse sand, 0 5 mm to 2 mm, ϕ=-1.0 to 1.0) than the surrounding areas. In the October 2000 data (Fig. 8a), they contained symmetric ripples with a wavelength of ~2.5 m and height of ~0 3 m. In the May 2001 data (Fig. 8b), their wavelength is roughly half and they have rotated by ~30° towards a more east-west orientation. The symmetric nature of the ripples suggests that they were probably formed by wave motion.

Very few rocks, or similar obstacles, were observed in the survey area, though boulder fields were seen to the south of the survey area during turns An example of a rock can be seen in Figure 8 and it appears to be have been partially buried in the time interval from October 2000 to May 2001. All of the aforementioned observations, clearly indicate that the seabed at this location is dynamic. If a characterization of the bed forms is necessary to understand the roughness parameters for seabed scattering, then this characterization must be done coincident with the scattering measurements. Further, these observations have implications for marine engineering as the seabed may have been assumed to be quiescent at this depth.

III. Geo-acoustic and Geo-technical Properties

Geoacoustic properties of the seabed are required for modeling the reverberation and propagation data collected during the Boundary 2001 sea-trial. DREA is pursuing two methods for obtaining this information The first is using the wide angle seismic reflection and bottom loss (WARBLE) technique of Holland and Osler [3] using a towed source (GeoAcoustics boomer plate) and moored receiver (UAT). The second method is direct *in-situ* measurements using a free fall cone penetrometer (FFCPT) that is under development and will eventually carry optional geoacoustic modules (*e.g.* resistivity).

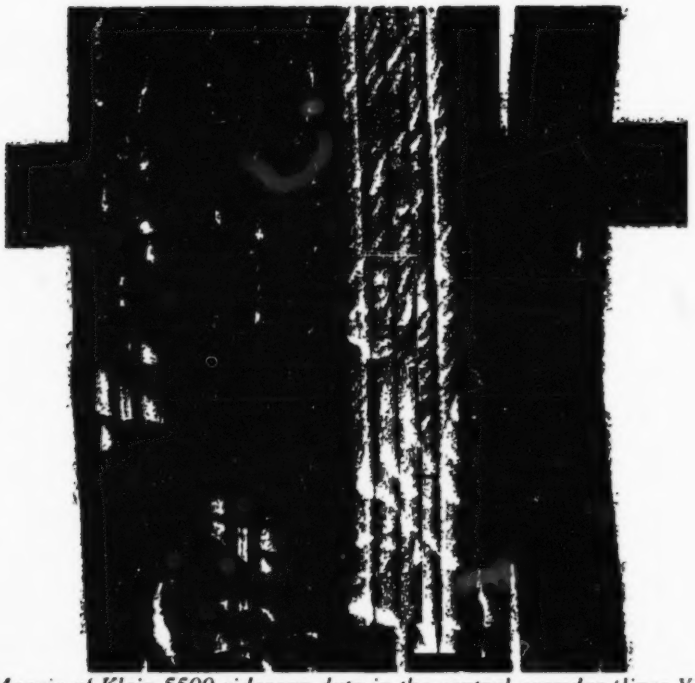

Figure 6: Mosaic of Klein 5500 sidescan data in the central corridor (lines Y-Z, U-V, E-F, W-X, AA-BB, and yellow box in Fig. 3). There is an extensive series of parallel ribbons oriented northeast to southwest and quasi-orthogonal patches with higher scatter (the seabed depressions) Width of the image is 2300 m.

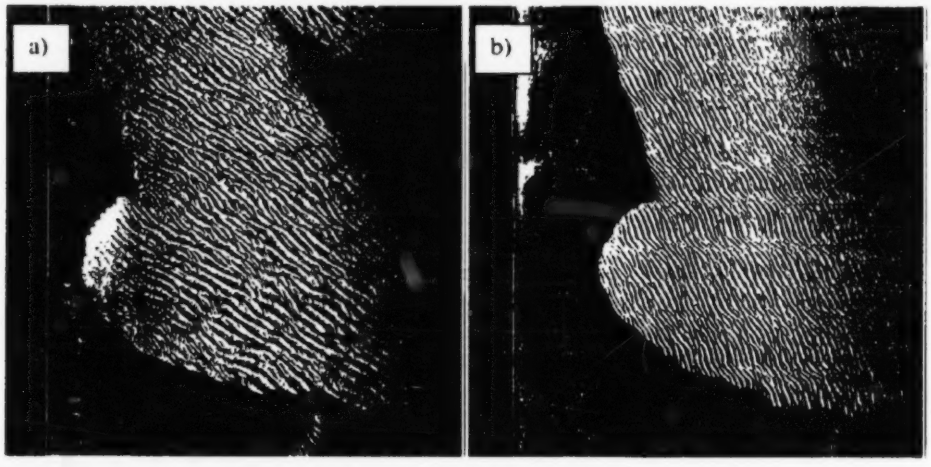

Figure 7: Klein 5500 sidescan images on line G-H from a) October 2000 and b) May 2001. The wavelength and orientation of ripples has changed Width of images is 150 m

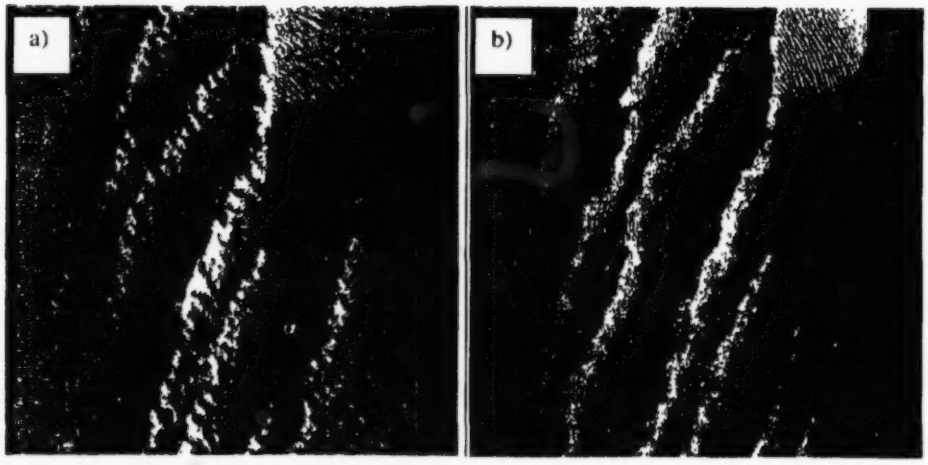

Figure 8: Klein 5500 sidescan images on line G-H from a) October 2000 and b) May 2001 The mega-ripples superimposed on the ribbons have decayed and the rock has been more deeply buried. Width of images is 150 m.

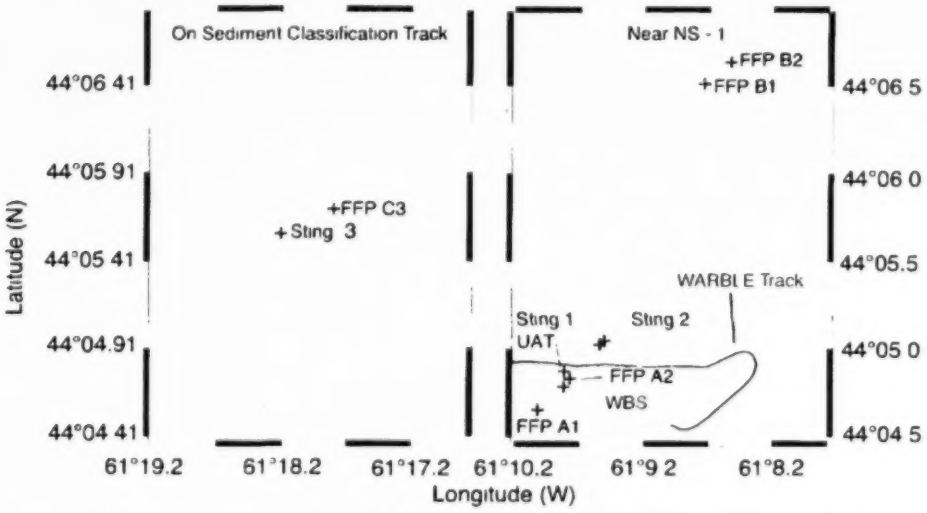

Figure 9: Location map of the WARBLE run and penetrometer (FFCPT and STING) drops near NS-1.

The location of the WARBLE run, FFCPT drops and seabed terminal impact naval gauge (STING) drops near NS-1 are displayed in Figure 9. FFCPT and STING drop locations were selected to include: the depressions with high scatter, the area where WBS mono-static and bi-static experiments were conducted, and an area where NRV Alliance

conducted some direct path scattering measurements. Results from the WARBLE run are not yet available.

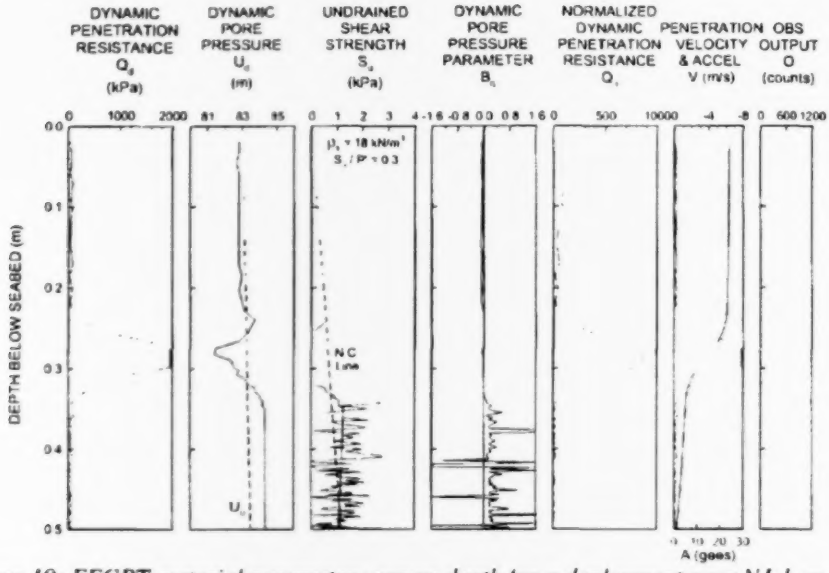
DYNAMIC PENETRATION RESISTANCE Q_d (kPa)
DYNAMIC PORE PRESSURE U_d (m)
UNDRAINED SHEAR STRENGTH S_u (kPa)
DYNAMIC PORE PRESSURE PARAMETER B_q
NORMALIZED DYNAMIC PENETRATION RESISTANCE Q_t
PENETRATION VELOCITY & ACCEL V (m/s)
OBS OUTPUT O (counts)
DEPTH BELOW SEABED (m)
N.C. Line
A (gees)

Figure 10: FFCPT material parameters versus depth for a deployment near NJ-1 on the ONR Strataform. Analysis provided by Christian Situ Geoscience Inc.

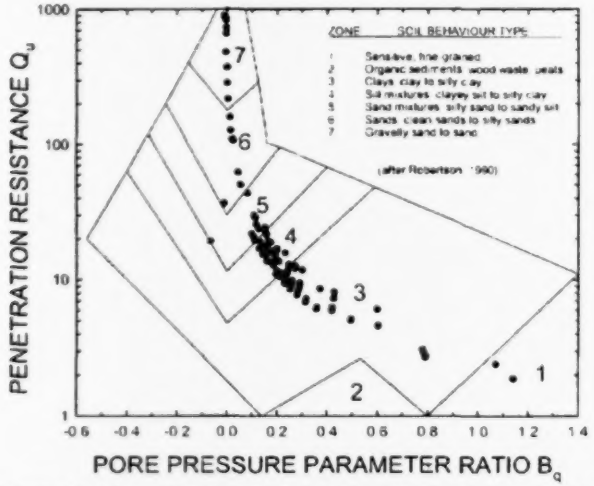
ZONE SOIL BEHAVIOUR TYPE
1 Sensitive, fine grained
2 Organic sediments: wood waste, peats
3 Clays: clay to silty clay
4 Silt mixtures: clayey silt to silty clay
5 Sand mixtures: silty sand to sandy silt
6 Sands: clean sands to silty sands
7 Gravelly sand to sand
(after Robertson, 1990)
PENETRATION RESISTANCE Q_u
PORE PRESSURE PARAMETER RATIO B_q

Figure 11: Sediment classification chart using penetration resistance and pore pressure parameter data displayed in Figure 11. Marine sediment types range from clays (3), through silts(4) to sand (5) and gravels (7). Dots are color coded from violet at the surface to red at depth `Analysis provided by Christian Situ Geoscience Inc.

The FFCPT is a free fall probe that has been developed to measure geotechnical and geoacoustic properties of the seabed [4]. Its combination of geotechnical sensors, acceleration, pore pressure, hydrostatic pressure, and optical backscatter, represents a significant advance over acceleration-based penetrometers, such as the expendable bottom penetrometer (XBP), and permits the direct application of geotechnical analysis methods and parametric-based correlations already long established in engineering practice. It provides two independent means of calculating the undrained shear strength [4] and utilizes a standard CPT-based sediment classification chart as part of the interpretation algorithm [5]. Near NJ-1 (39°14.949N, 72°51.798W) on the ONR Strataform area, the FFCPT has detected and measured the geotechnical properties of a pervasive near surface sand layer that is in between clay and silt layers (Figs. 10 and 11) Similar analyses will be conducted near NS-1 on the Scotian Shelf, though the depth of penetration is limited by the diameter of the prototype FFCPT and the hardness of the sand seabed.

IV. Conclusions

DREA has collected geoacoustic data to characterize the experimental areas for the Boundary 2001 sea-trial, with particular emphasis on Site NS-1 on Sable Island Bank, Scotian Shelf, Nova Scotia. Measurements include bathymetry, vertical incidence seismic reflection, sidescan sonar, geoacoustic properties from WARBLE inversions, grab samples, and *in-situ* data using a prototype cone penetrometer that is being modified to carry geoacoustic sensor modules. At NS-1, there is an extensive series of flow parallel ribbons intersected by quasi-orthogonal depressions. The depressions are erosional patches that are composed of coarser grained material, contain wave formed ripples, and manifest themselves as having higher scatter at vertical incidence and at shallow grazing angle. The seabed at NS-1 is dynamic as bed forms observed in October 2000 have rotated or been destroyed in the time interval until the repeat survey in May 2001. This may have implications for acoustic scattering experiments that rely on quantitative roughness parameters of the seabed and marine engineering projects that may have been assumed that the seabed is quiescent at this depth.

V. Acknowledgements

The author would like to acknowledge the contributions from the following groups and individuals: the Mine Counter Measures group at DREA for assistance in collecting the sidescan data; the Canadian Forces Route Survey office for assistance in sea-trials and preparing a mosaic of the sidescan data, the Canadian Hydrographic Service and Geological Survey of Canada-Atlantic for permission to use their bathymetric compilation; Dr. Ned King and Dr. Michael Lee of the GSC-Atlantic for assistance in interpreting the sidescan data and sediment dynamics; and Brooke Ocean Technology and Christian Situ Geosciences for material concerning the free falling cone penetrometer.

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DREA oceanographic and atmospheric environmental data for Boundary 2001

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Abstract

A range of environmental data was collected by DREA in support of the Boundary 2001 experiment which took place from May 14 to June 1, 2001 at Strataform off New Jersey and on the Scotian Shelf. Some satellite data was also obtained in support of the Geoclutter experiment which took place from April 26 to May 7, 2001 at Strataform. The environmental data falls into three main categories: satellite imagery, meteorological data and oceanographic data. An overview of available data and description of instrumentation is presented.

Synoptic data

Visible and infrared imagery from NOAA's GOES8 (Geostationary Operational Environmental Satellite) was obtained from Environment Canada to provide a synoptic overview of weather conditions along the north-east coast of North America. Imagery was recorded every half hour for the period 1 to 31 May, 2001 covering both the Geoclutter and Boundary 2001 experiments. GOES imagery can also be obtained directly from NOAA's Geosynchronous Satellite Server at http://www.goes.noaa.gov/ where imagery is archived for up to three weeks.

The synoptic weather picture provided by the GOES8 imagery was augmented with one-day weather forecasts and one-day forecasts of surface waves from Environment Canada. Wave forecasts are produced by the WAVEWATCH III model developed at NOAA. The weather and wave forecasts are a convenient record as they are available in digital form while being reasonably accurate since they are one-day forecasts. More accurate hand-annotated weather and wave synopses could have been obtained but would have had to be digitized, an effort that was not considered necessary.

The final element of the synoptic environmental picture is the sea surface temperature (SST) imagery from the Advanced Very High Resolution Radiometer (AVHRR) sensor aboard the NOAA Polar Operational Environmental Satellites (POES). The SST data was obtained from the Johns Hopkins University Ocean Remote Sensing website at http://srbdata.jhuapl.edu/d0043/avhrr/gs. SST imagery was saved as single pass images and 3-day composites. Examples of synoptic data are shown in Fig. 1 for May 20, 2001.

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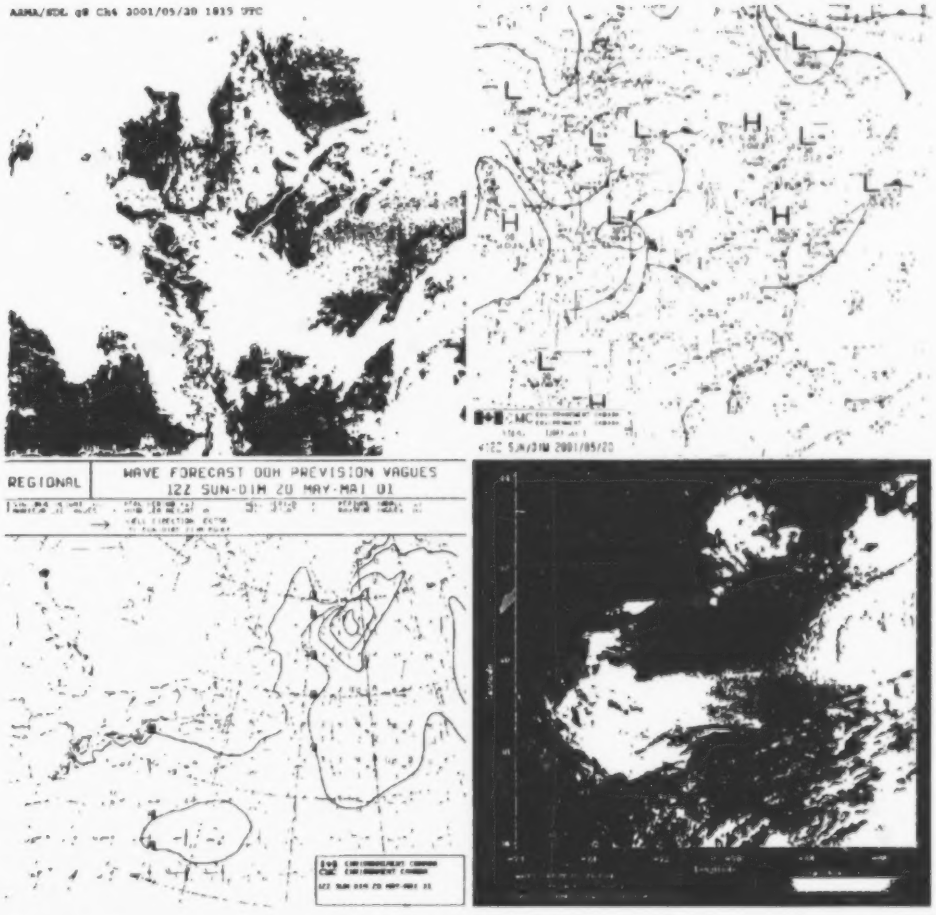

Figure 1 Synoptic data for May 20, 2001. Clockwise from top-left: GOES8 IR image, surface meteorological forecast, sea surface temperature and WAM surface wave forecast.

SAR satellite imagery

In addition to the wide area SST and GOES satellite imagery, imagery was obtained from Synthetic Aperture Radar (SAR) instruments aboard the Canadian Radarsat-1 and European ERS-2 satellites. The ability of space-based SAR to detect ships and estimate surface wind over the ocean is well documented (Refs.1-4) Furthermore, the brightness of a ship radar signature and analysis of the wake signature, when visible, can provide an estimate of the ship size, speed and direction. This information combined with estimates of surface winds can be used as inputs for ambient noise models. A summary of ship detection and wind estimate capabilities of space-based SAR can be found in Ref. 5.

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Radarsat-1 and ERS-2 data, summarized in Table 1, was obtained by DREA and processed to backscatter image and ship/wind data products by the Canada Centre for Remote Sensing, Ottawa, Ontario. Data products were derived from Radarsat imagery using the Ocean Monitoring Workstation described in Ref. 2. An example of backscatter image and data products is shown in Fig. 2 for the Radarsat-1 image of May 3, 2001. Note that the solution for wind direction has a 180° ambiguity which must be resolved with additional information about the local wind direction.

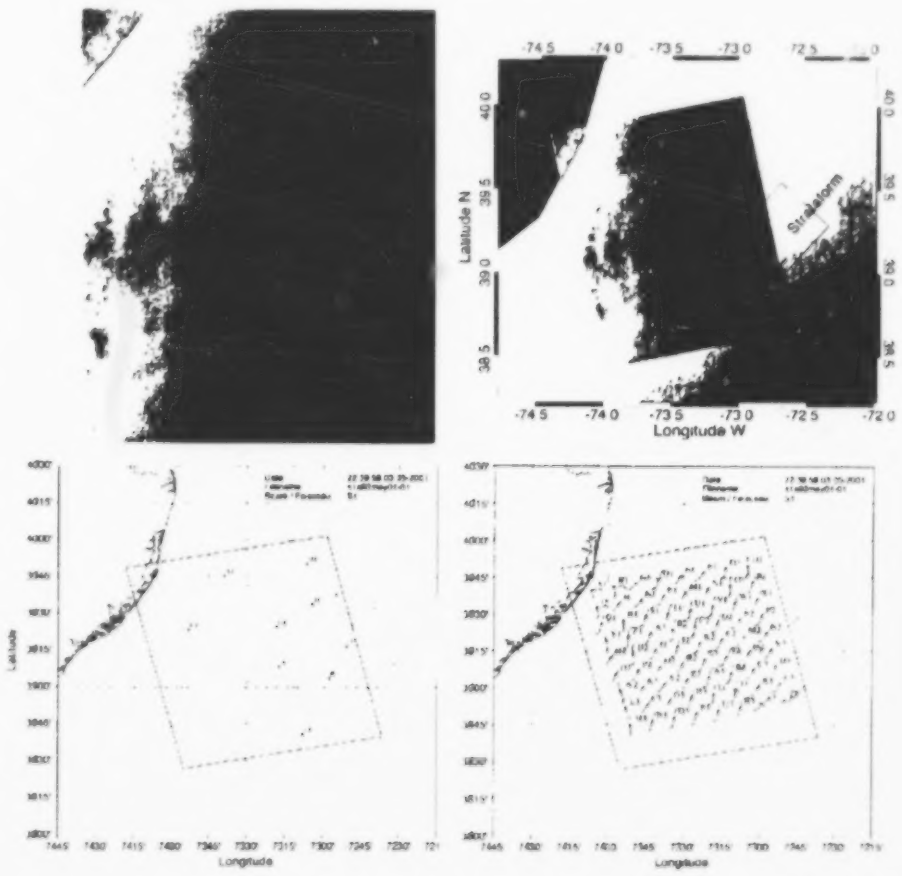

Figure 2 Radarsat-1 imagery and data products for 3 May, 2001 over Strataform area. Clockwise from top-left: Low-resolution backscatter image, backscatter image superimposed on bathymetry and coastline (New Jersey), wind detection product and ship detection product.

Table 1: SAR satellite imagery

date	time (UTC)	center lat (deg)	center lon (deg)	orbit	swath (km)	res. (m)	plat-form	beam mode
01/05/01	15:34 00	39.166	-72.633	Asc	100	25	ERS2	n/a
01/05/03	22:40 18	39.286	-72.735	Asc.	100	30	RSAT1	S2
01/05/10	22:36 10	39.434	-72.485	Asc	100	30	Rsat1	S1
01/05/11	03:07 00	39.417	-73.000	Dsc.	100	25	ERS2	n/a
01/05/17	22:31 55	39.273	-72.504	Asc	170	36	Rsat1	EXTL1
01/05/18	10:45.47	39.166	-72.705	Dsc.	100	30	Rsat1	S7
01/05/21	10:58 18	39.178	-72.918	Dsc.	100	30	Rsat1	S3
01/05/26	10:10 46	44.053	-61.301	Dsc.	100	30	Rsat1	S5
01/05/29	21 42 54	44.130	-61.383	Asc.	170	36	Rsat1	EXTL1
01/05/31	14:50 00	43.600	-60.600	Asc	100	25	ERS2	n/a

One reason the SAR data was obtained was to monitor the presence of internal waves during the trial. Internal waves have a signature in SAR imagery because they induce a slight modulation of the surface wave spectrum. The linear features in the south-west part of the backscatter image of Fig. 2 resembles an internal wave but, due its long wavelength and timing within the tidal cycle, it is believed to be due to an atmospheric internal wave. None of the SAR imagery exhibited any features that could be attributed to ocean internal waves. Although the Strataform area is known for strong internal wave activity in the summer months (Ref. 6) it was hoped that the relatively poor stratification of the water column typical of the winter and spring would minimize internal wave activity. This expectation is supported by the SAR satellite imagery.

***In situ* environmental data**

A range of *in situ* environmental measurements were made with instrumentation deployed from Quest. Equipment included an autonomous ocean profiling instrument known as Seahorse, a meteorological buoy for surface met data, two 300 kHz acoustic Doppler current profilers (ADCP), ambient noise measured with a variety of sonobuoys and the underwater acoustic target (UAT) described in Ref. 7, a ship-board 120 kHz echo-sounder and the Quest's own meteorological sensors. Figure 3 illustrates the availability of DREA's environmental data. A detailed list of deployment times and locations is given in Table 2. A summary of data from the Seahorse, met buoy, ADCPs is presented in this section.

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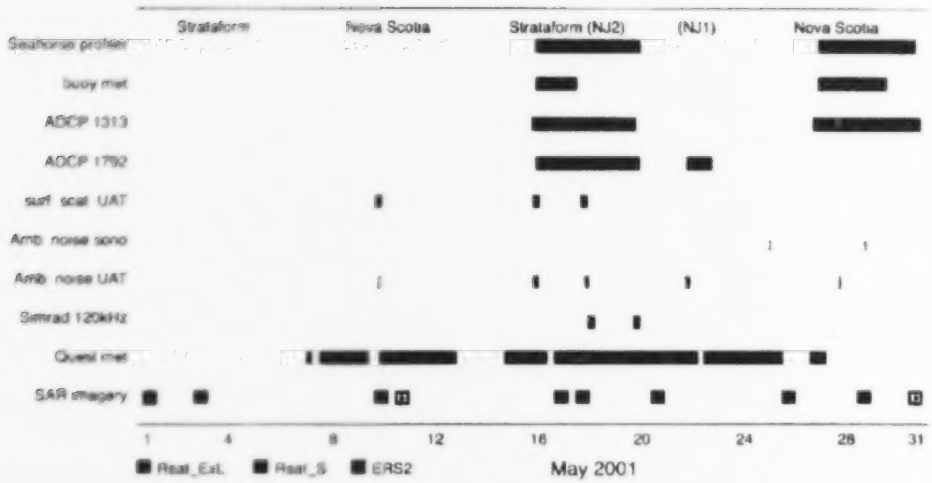

Figure 3 Q259 environmental dataset summary chart

Table 2: Times and locations of Q259 environmental measurements

instrument	stn.	location	depth (m)	deployed (utc)	recovered (utc)	comments
Seahorse profiler	NJ2	39 03 43N, 73 05 41W	80	May 16, 17 39	May 20, 14 15	-
met station	NJ2	39 03 43N, 73 05 41W	80	May 16, 17 39	May 18, 07:48	recording failed
ADCP 1313	NJ2	39 04 58N, 73 05 92W	70	May 16, 12:37	May 20, 12:45	-
ADCP 1792	NJ2	39 04 95N, 73 07 33W	74	May 16, 13 42	May 20, 17:00	-
ADCP 1792	NJ1	39 15 76N, 72 53 82W	77	May 22, 14:00	May 23, 14:32	-
ADCP 1313	NS1	44 03 66N, 61 11 36W	71	May 27, 11 49	May 31, 14:00	-
Seahorse profiler	NS1	39 03 43N, 73 05 41W	66	May 27, 18:27	May 31, 12.14	-
met station	NS1	39 03 43N, 73 05 41W	66	May 27, 18:27	May 30, 11 12	recording failed
surf. scat., UAT	NS1	44 03 66N, 61 11 36W	73	May 10,12:42	MAY 10,12:43	cardiod up
surf. scat., UAT	NJ2	39 03 38N, 73 07 01W	70	May 16, 16:23	May 16, 16 24	cardiod up
surf. scat., UAT	NJ2	39 03 38N, 73 07 01W	70	May 18, 14:02	May 18, 14:38	cardiod up
Amb. noise, sono	NS1	43 23 0 N, 64 42.70W	~70	May 25, 22:19	May 25, 22:25	quiet state
Amb. noise, sono	NS1	44 05 30N, 61 08.80W	~70	May 29, 09:49	May 29, 10:50	Rsat overpass
Simrad 120kHz	NJ2	around NJ2	~80	May 17, 20:40	May 17, 22:44	slight int. waves
Simrad 120kHz	-	NJ2 to NJ1	~80	May 20, 17:45	May 20, 19:45	-
Quest met	-	continuous	-	May 07, 22:00	May 31, 11:05	-

Acoustic Doppler current profilers

Two RD Instruments acoustic Doppler current profilers (ADCPs) were deployed during Boundary 2001. The instruments are both Model WHS300 "Workhorse Sentinel" which operate at 300 kHz. The ADCPs are autonomous instruments that measure acoustic backscatter, ocean current speed and current direction as a function of depth in the water column. Both ADCPs were fitted with additional firmware from RD Instruments to enable surface wave spectra to be measured. The ADCPs were mounted in a buoyant body called a "Streamlined Underwater Buoyancy System" (SUBS) tethered approximately 2 m from the sea bed. Once deployed, the instruments are free to rotate in response to currents. On-board compass and tilt meters measure the orientation of the ADCP enabling the vertical profile of current and its absolute direction to be resolved. The ADCPs are rated for use at depths up to 175 m although the pressure housings are rated for 500 m. The ADCPs can be left to make measurements at preprogrammed intervals for periods of up to one month. The data are recorded in on-board solid-state memory modules. Data are retrieved upon recovery. Profiles measured during Boundary 2001 were recorded every minute with a vertical resolution of 1-m.

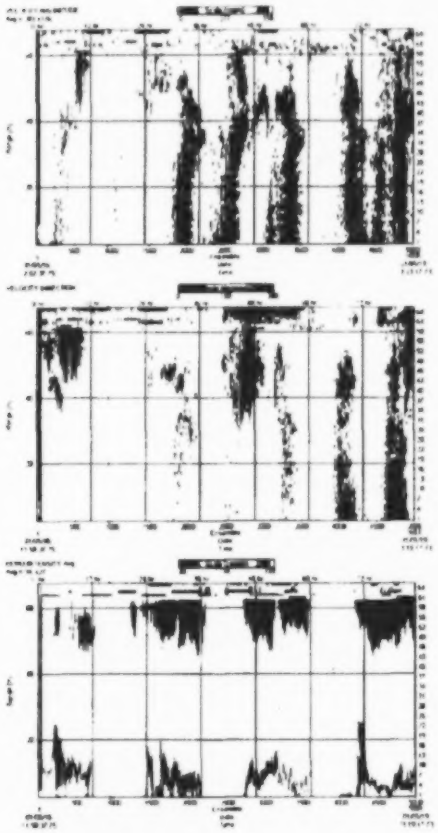

Figure 4. *ADCP data recorded at Strataform site NJ2 (39°03.4' N, 73°07.2' W). From top to bottom plots are: current magnitude, current direction and backscatter intensity.*

Figure 4 is an example of data from one of the ADCPs (good luck serial no. 1313) deployed at Strataform site NJ2 from 16 to 20 May, 2001. The upper two plots are current magnitude and direction which show circular tidal flows typical of the continental shelf. Baroclinic behavior where tidal circulation above and below the thermocline are out of phase is also typical of continental shelf waters. The bottom plot shows relative backscatter intensity at 300 kHz. A pronounced diurnal cycle can be seen where the backscatter increases every evening at dusk (times 12h, 36h and 60h on the backscatter plot). This is due to the nightly ascent of marine micro-organisms and fish to shallower depths.

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Meteorological buoy

Sea surface meteorological measurements were made with a met station located on the Seahorse buoy. The system was manufactured by MetOcean Inc. (www.metocean.com), Dartmouth, NS. Measured parameters are wind speed and direction, barometric pressure, air temperature, and water temperature. Data are stored as one-minute averages in Flash-Card memory and are retrieved upon recovery of the buoy. For Boundary 2001, surface meteorological measurements were made to support surface acoustical scattering experiments and to monitor sea surface conditions to aid interpretation of SAR satellite imagery. An example of surface met data from site NJ2 on Strataform is shown in Fig. 4.

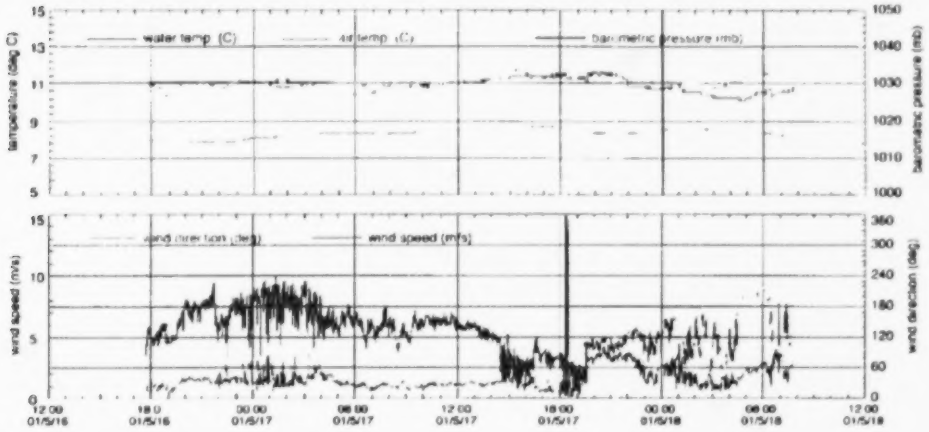

Figure 4. Surface met data from Strataform site NJ2 (39°03.4' N, 73°07.2' W).

Seahorse moored ocean profiler

The Seahorse is an autonomous profiling system for continuous conductivity, temperature and depth (CTD) measurements of the water column. It is manufactured by Brooke Ocean Technology Ltd. (www.brooke-ocean.com), Dartmouth, NS. The Seahorse sensor package is a Sea-Bird SBE-19 CTD. The Seahorse rides along a cable between a surface float and a mooring anchor and is designed for use to depths of 200 m. The system takes advantage of the wave-induced motion of its surface float to ratchet the profiler down the cable. When the Seahorse reaches a stop at the bottom of the cable it waits for a programmed period of time then releases the ratchet mechanism and floats to the surface using the cable as a guide. The CTD profile is acquired during the ascent. A schematic of the deployed configuration is shown in Fig. 5. Data is stored on board the Seahorse for later downloading to a PC when the instrument is recovered. Data obtained with the Seahorse at the Strataform NJ2 site is shown in Fig. 6. The salinity is derived from the measured conductivity using analysis software provided by Sea-Bird. The salinity, pressure and water temperature are used to calculate the density and sound speed profiles.

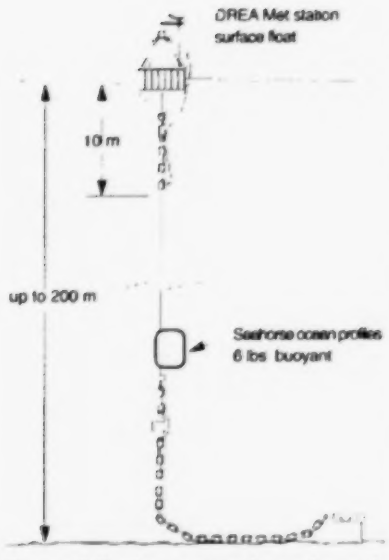

Figure 5 Seahorse mooring schematic showing met station on surface float.

Several observations can be made about the data displayed in Fig. 6. First, after May 17, the seahorse failed to go all the way to the bottom of its mooring before beginning its ascent and profile measurement. This was due to unusually calm weather conditions that resulted in a sea state of zero and flat calm water. Since the Seahorse relies on motion of its surface float to make the instrument go down, it was unable to descend during the calm period which lasted several days. Deeper profiles could have been maintained if the Seahorse had been programmed for longer intervals between profiles thus giving it more time to travel downward. For the NJ2 deployment the Seahorse was programmed to do a profile every 20 minutes. When the Seahorse was deployed a second time on the Scotian Shelf, it was programmed to do a profile every 30 minutes. On the Scotian Shelf deployment the Seahorse made 283 complete profiles.

The calm period beginning on May 17 may be associated with a saline water mass from the edge of Gulf Stream. SST imagery on May 17 and 20 indicates that the surface water temperature around the NJ2 site had a complicated structure with variations of up to 4°C. This suggests the influence of the Gulf Stream but the surface temperature measured by the Seahorse and met buoy were stable at around 10 - 11°C. SST imagery between May 17 and 20 was obscured by cloud. The Seahorse results and XBT and CTD measurements of other ships involved in Boundary 2001 indicate a great deal of variability in the oceanography at Strataform (Refs. 8, 9).

The salinity plot in Fig. 6 exhibits some spurious high-salinity areas late on May 17. These result in what appear to be instabilities visible on the density plot. It is believed that the spurious salinity readings are an artifact related to the vertical distance between the conductivity and temperature sensors on the Sea-Bird SBE-19 CTD (Ref. 10). Since the sound speed depends almost entirely on temperature, the artifacts in the salinity measurements do not appear in the sound speed plot.

A series of oscillations visible in all plots of Fig. 6 during the first half of May 16 is a low amplitude internal wave aliased to a low frequency by the 20-minute sampling interval of the Seahorse. The sound speed profile plot appears to be nearly identical to the temperature plot as is expected since the sound speed only depends on salinity to third order.

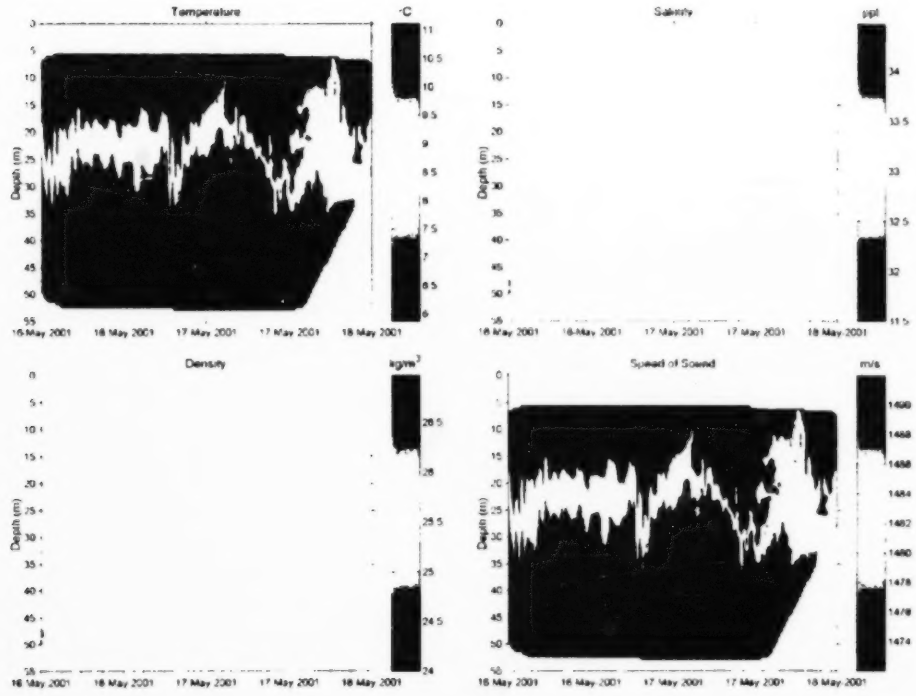

Figure 6. Seahorse data obtained at the Strataform site NJ2 (39°03.4' N, 73°07.2' W).

Summary

An overview of the environmental data collected by DREA during the Boundary 2001 experiment was presented. Synoptic data consisting of GOES satellite imagery, AVHRR sea surface temperature imagery, weather charts and WAM wave prediction charts are available for the entire month of May and cover part of the GeoClutter trial. Rarersat1 and ERS2 synthetic aperture radar imagery was obtained and processed to backscatter image, ship detection and surface wind products. An overview of the SAR imagery indicates that there little internal wave activity, an observation that is consistent with ship-board echo-sounder data. A series of successful deployments of oceanographic instruments was achieved during the trial including a surface met station, the Seahorse autonomous ocean profiler and ADCPs. The oceanographic data is being used to characterize the acoustic propagation environment prevailing during the experiment as part of on-going analysis.

Acknowledgements

The authors would like to thank Mark O'Connor, DREA for his efforts in programming, deploying and processing data from the met buoy, Seahorse and ADCPs. The contribution of designing, building and deploying many of the moorings by Roger Arsenault, DREA is greatly appreciated. Patric King of Environment Canada, Downview, ON assembled the GOES8 imagery and Serge Desjardins, Environment Canada, Dartmouth, NS provided the weather and wave forecasts. Finally, the authors would like to thank James Hamilton of the Bedford Institute of Oceanography, Dartmouth, NS for preparing the visualization of the Seahorse data shown in Fig. 6.

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Boundary 2001 REA: Model-Data Comparisons at the Strataform and Scotian Shelf Sites using GSM and Manual Fits to the Reverberation Data

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Abstract
During the Boundary 2001 experiment, long-range reverberation data were collected on several SACLANTCEN towed horizontal line arrays. This report uses some of that data, and compares it with model predictions from the Generic Sonar Model. To achieve the agreement, the bottom loss and scattering functions were manually adjusted to produce a reasonable fit to the data. All the work was conducted at sea during the trial period, so the results can be considered the output from a REA (Rapid Environmental Assessment) exercise, similar to the approach used by Ellis *et al* [SACLANTCEN Report SR-280, 2000] in the NATO REA exercises Rapid Response. The estimates can now be compared with other results from the experiment, namely direct scattering measurements, and more sophisticated inversion techniques such as simulated annealing.

Introduction

Boundary 2001 was the second sea trial in a three-year Joint Research Program between Canada, the United States, and SACLANT Undersea Research Centre (SACLANTCEN). The purpose of the program is to make direct measurements of the boundary interactions – scattering and bottom loss in particular – that affect low-frequency reverberation in shallow water. A further aspect of the analysis is the comparison of the direct measurements with the estimates of bottom loss and scattering extracted from model-data comparisons between reverberation data and model predictions. Our contribution is the latter part.

Most of the work will be presented elsewhere by other authors. This paper describes the model-data comparisons and bottom estimates obtained at sea during the sea trial from 10 May to 2 June 2001. This is very much a REA (Rapid Environmental Assessment) approach, with procedures very similar to those done during the Rapid Response series of experiments [1, 2], and the Boundary 2000 experiment. A manual inversion procedure, using simple bottom loss and backscattering parameters together with the Generic Sonar Model (GSM) [3], was used [4]. Better fits to the data can be obtained [5, 6], using a more complicated bottom model and a simulated annealing approach, this was not attempted at sea.

As in previous experiments, the data were gathered on horizontal line arrays towed behind the NATO Research Vessel *Alliance*. Generally a five-sided "petal" pattern was used, to resolve the left-right ambiguity of the array. Details of the procedure are given in Ref. 4. The main receivers were the SACLANTCEN 256-m LF (low-frequency)

Prakla array and the 32-element 5.6-m MF (mid-frequency) array; these were deployed as a dual tow. The sources were 0.8-kg SUS charges. During Boundary 2001, three petal-patterns were run, two on the Stratform region off the United States New Jersey coast, and one on the Canadian Scotian Shelf between Halifax and Sable Island. This report describes some model-data comparisons for three petal patterns. As mentioned before, all the data analysis and model predictions were performed at sea, so the latter site, done in the last few days of the trial, had very little time devoted to modelling it. Other data were taken using the SACLANTCEN Atlas source and cardioid array, but not analysed at sea.

Petal-pattern P02 (Strataform Site C1.5)

The water depth for petal pattern P01 was too shallow to deploy the 90-m SUS charges, so only the Atlas source and MF array were used, these data were not available at sea for modelling. Petal pattern P02 was run on 15 May, centered at N 39° 16.0' W72° 43.0' in about 118 m of water. The headings on the legs of the petal pattern are 139°, 002°, 220° (rerun at 036°), 070°, and 289°; the compass on the Prakla (LF) array was not working, so the heading estimates are from records of the ship heading. The Prakla array was initially deployed at a depth of 15 m (5 turns on the winch), rose to 5 m on the initial leg 3, then was lowered to 30 m (10 turns) for the remaining legs. The MF array was deployed with 19 turns, later 38 turns, its depth was close to that of the LF array. Two 90-m SUS charges were dropped on each leg, for the first charge the gains on the LF array were initially 18 dB, and changed to 36 dB after about 10 s; for the second SUS the gain was initially 0 dB, then changed to 36 dB. On the MF array the gains were 12 and 24 dB respectively for the first SUS, and 0 dB and 24 dB on the second SUS. The sea state was about Beaufort 4 during the experiment.

Figure 1 shows the XBTs near site P02 on the day of the experiment. The XBTs seem to be spatially dependent, and more dependent on the water depth than on temporal variability. A more extensive survey of the XBTs was conducted by Baldasserini [7].

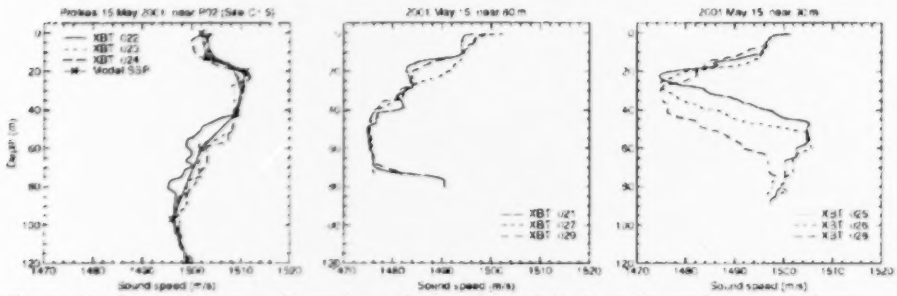

Figure 1 On the left, sound speed profiles, and simplified profile used for modelling. The other two figures show profiles at two shallower water depths.

Figure 2 shows the reverberation on the broadside beams from each leg at 350 Hz (maximum array aperture and resolution) Some of the spikes around 10 seconds are related to the gain change (18 to 36 dB). The reverberation traces from all 5 headings are remarkably consistent, except near 30-50 seconds, where shelf-break features seem to be causing enhanced reverberation

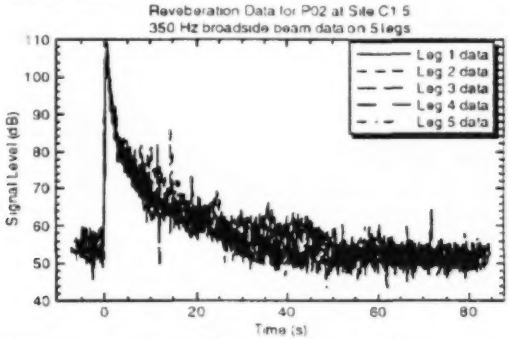
Reveberation Data for P02 at Site C1 5
350 Hz broadside beam data on 5 legs
Leg 1 data
Leg 2 data
Leg 3 data
Leg 4 data
Leg 5 data
Signal Level (dB)
Time (s)

Figure 2 Broadside beam data in 350 Hz band, on all 5 legs of petal pattern P02.

For modelling, a half-space model was chosen for the bottom loss, after adjusting the parameters to fit the 630 Hz data, the acoustic parameters were chosen to be sound speed 1650 m/s, density (relative to water) 1 7, and attenuation 0 5 dB/m-kHz The reflection loss is shown in Fig 3a Reasonably good fits to the data were obtained using the Generic Sonar Model, and varying the strength of the Lambert scattering coefficient for the various frequencies Figure 3b shows a typical scattering function used in the modelling, in this shallow-water environment, the steep-angle facet strength and width are not determined by the data, and are program defaults. For computational efficiency, the monostatic mode of GSM was used, with source and receiver at the array depth of 30 m

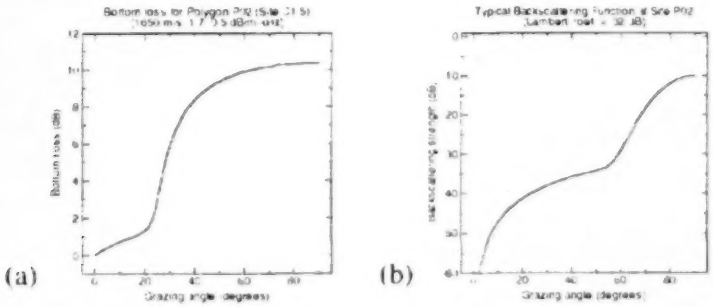

Figure 3. (a) Bottom reflection loss curve, corresponding to the geoacoustic halfspace; (b) typical backscattering function, with a Lambert scattering coefficient of –32 dB, the steep-angle dependence is due to our default values, and not determined from the data.

Various model-data comparisons are shown in Figs. 4 and 5, for several beams at 630 Hz, and for the broadside beam at 160, 350, 630, and 1400 Hz. With the constant geoacoustic half-space, there seems to be an increase in the scattering with frequency, see Table 1. There is also an indication that the bottom loss should be higher at lower frequencies and less at higher frequencies. With a half-space model, that would require a lower sound speed, (or higher attenuation) at low frequencies, this is not what one might expect. It may be that there is is a more reflective (higher sound speed) layer near the surface, and lower sound speed below. The details of an optimum solution are beyond the "manual inversion" approach, and best left to direct measurements [8] or simuated annealing [6] to determine a set of parameters that fit the data.

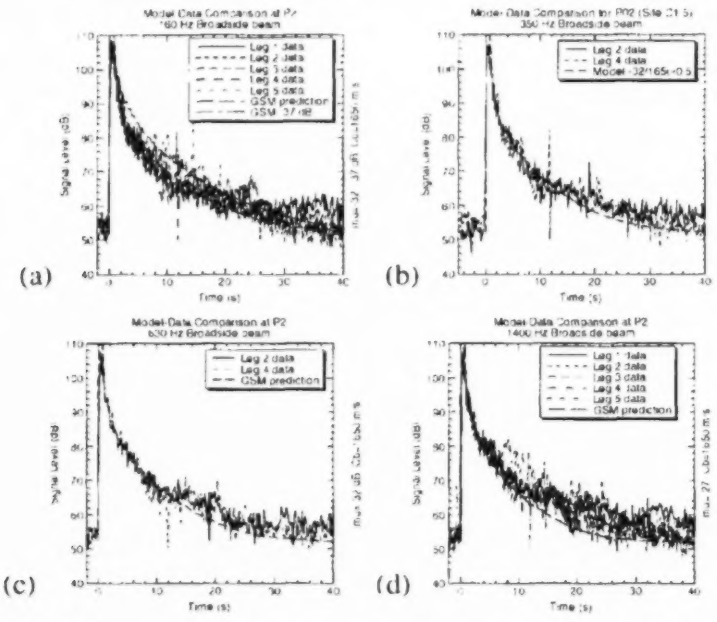

Figure 4 Model data comparisons at various frequencies for the broadside beam. (a) 160 Hz, (b) 350 Hz; (c) 630 Hz, (d) 1400 Hz. The geoacoustic model was determined with the 630 Hz data, and for the other frequencies only the scattering strength was adjusted. Note that for 160 Hz, other bottom loss fits were tried

To get a feeling for the overall quality of the predictions over all beams, the model-data differences at 350 Hz are plotted in Fig. 6, and overlain on the bathymetry. The fits at short times (ranges) are reasonably good (0 dB, the blue-"orange" colour transition). To the right aft of the array heading (black arrow), note the high scattering starting just beyond the shelf break, it also appears on the ambiguous beam. These range-dependent features are not treated in the flat-bottomed model that we are using.

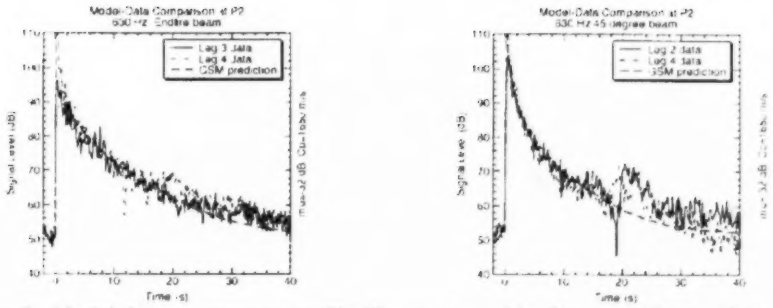

Figure 5 Model data comparison at 630 Hz, for aft endfire beam and beam 45 degrees from aft endfire.

Frequency (Hz)	Lambert Coefficient (dB)
160 Hz	–37
350 Hz	–32
630 Hz	–32
1400 Hz	–27

Table 1 Summary of scattering strengths from manual fit in petal pattern P02.

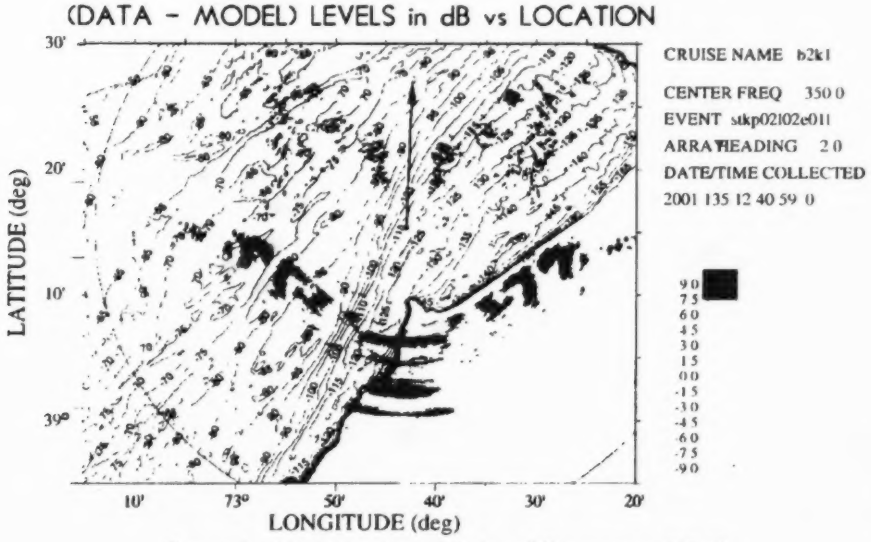

Figure 6. Polar plot of model-data differences at 350 Hz.

Petal Pattern P03 (Stratform Site C3)

Another petal pattern P03 was run on 17 May 2001 at Site C3, centered at N 39° 18' W 72° 31', in about 140 m of water. The ship's headings on the legs of the petal pattern were 152°, 199°, 054°, and 276°, only 4 legs were completed. On Leg 1 the LF array had a number of noisy hydrophones, on Legs 2, 3 and 4 the data quality was better. The LF array and MF arrays were deployed at about 70 m, with cable scopes of 26 and 97 turns respectively. The SUS nominal depth was 90 m, so an average depth of 80 m was used for modelling with the monostatic version of GSM.

The sound speed profile was nearly isovelocity, with some structure shallower than 60 m. Figure 7 shows two measured sound speed profiles, and the simplified composite used for modelling.

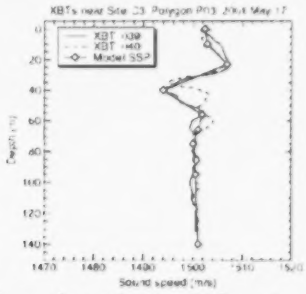

Figure 7 Measured sound speed profiles for P03, and composite used for modelling

Figure 8 illustrates the manual approach to obtain a match with the data from the broadside beam for petal pattern P03. Leg 1 was chosen since the broadside beam has the least interaction with scattering features on the shelf edge. The geoacoustic model for petal pattern P02 was the starting point, but falls below the data in the 5 to 20 s region. Two lower loss models were tried, one with a lower absorption coefficient 0.1 dB/m-kHz, and another with a higher sound speed, 1700 m/s. The first is clearly far off, and the second, although it improves things at short times, does not provide a good fit to the rate of decay of the reverberation. Increasing the Lambert coefficient to –30 dB from –32 dB seems to provide a better fit. Perhaps even more loss is called for to match the decay and provide a match beyond 20 seconds; the last two curves increase the loss by almost an identical amount, decreasing the bottom sound speed to 1630 m/s, or increasing the attenuation to 0.7 dB/m-kHz. Our best fit is essentially the same geoacoustic model as for P02, but with the attenuation increased from 0.5 to 0.6 dB-m/kHz.

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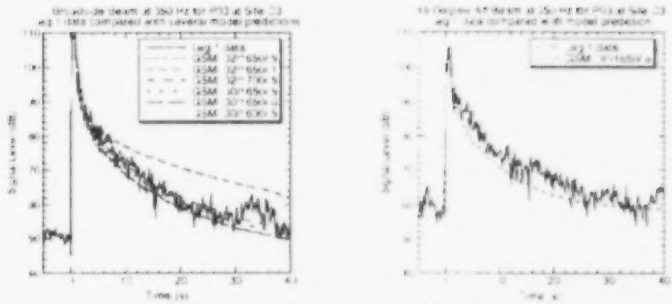

Figure 8. (a) Broadside beam data for petal pattern P03 compared with successive iterations of the manual procedure. (b) data from P02 for beam pointed 45° aft of broadside, compared with model prediction

Petal pattern P04 (Scotian Shelf)

Petal pattern P04 was conducted (mainly) on 29 May 2001 in the vicinity of Site C4, centered at N 44° 11.0' W 61° 8.5', on the Scotian Shelf, in about 80 water depth. The legs were at nominal headings of 153°, 018°, 219°, 084°, and 112°, (the final leg was run on 31 May, with both monostatic and bistatic sources). There were problems with the SUS charges, and foggy weather, so a number of the SUS drops were delayed and did not occur near the centre of the petal pattern. The DREA Research Vessel *Quest* dropped some SUS charges for bistatic measurements, and, to help align the LF array for monostatic measurements, provided a 2-s beacon ping at 1380 Hz, 157.6 dB re 1 µPa at 1m.

Figure 9 shows four sound speed profiles in the area, and a composite profile used in the modelling. The water depth used for modelling near Site C4 was 78 m. The SUS charges had a nominal detonation depth of 18 m, and the arrays were towed near 30 m depth, the source depth used in GSM was 21 m.

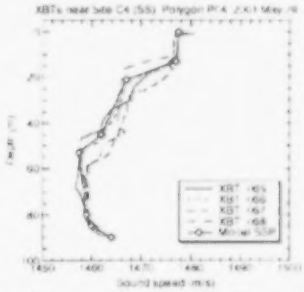

Figure 9. Sound speed profiles on Scotian Shelf, and composite profile used for GSM model predictions

Figure 10 shows some data from the broadside beam for two legs at 350 Hz. There were one or more seismic survey vessels in the area, booming loudly around 37 Hz and spilling over into much of the other spectrum. Leg 3 was particularly affected.

Figure 10 also shows an initial modelling attempt for the Site. The "Strataform" P02 bottom parameters seem to provide a reasonable fit to the data. The Lambert scattering coefficient is –32 dB, but due to the lower water sound speed at the bottom (1464 m/s vs 1499 m/s), the seabed sound speed is reduced to about 1610 m/s, the relative density (1.7) and seabed attenuation (0.5 dB/m-kHz) are not significantly changed. A slightly higher bottom loss (attenuation coefficient 0.6 dB/m-kHz) seemed to give a better slope to the reverberation time series. Other beams and frequencies need to be run to determine a better estimate of the bottom loss and scattering.

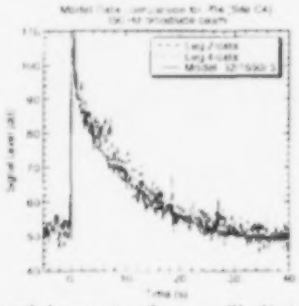

Figure 10. Initial data and model runs for Scotian Shelf, for broadside beam at 350 Hz.

Summary

The polar plots, e.g. Fig. 6, provide information about the anisotropy of the reverberation. At short times, these sites (by design) show much less anisotropy than any of the previous sites we have visited for REA analysis [1, 8].

The mean reverberation, and model predictions, were remarkably similar at all sites. A similar bottom model and scattering seemed to provide a reasonable fit at all sites, see Table 2 for 350 Hz. As indicated in Table 1, Site P02 indicated a frequency dependence of the scattering strength. The frequency analysis was not done for the other sites.

Site	Relative Density	Sound Speed	Attenuation Coefficient	Lambert Coefficient
P02 / Site C1.5	1.7	1650 m/s	0.5 dB/m-kHz	–32 dB
P03 / Site C3	1.7	1650	0.6	–30
P04 / Site C4	1.7	1610	0.5	–32

Table 2. Summary of extracted properties at 350 Hz.

Due to our data processing parameters and limited dynamic range of the measurement system, a measure of the high-angle bottom properties was not possible in these shallow water sites.

We found the manual inversion procedure more difficult at the Boundary 2001 sites compared to previous sites, perhaps because of the relatively shallow water. It may be that the reverberation data do not contain much information about the bottom properties other than a low-angle "dB per degree" for the bottom loss, and a simple measure of the scattering, such as the Lambert coefficient.

All the work was conducted at sea during the trial period, so the results can be considered the output from a REA (Rapid Environmental Assessment) exercise similar to the approach used in Rapid Response [4]. They can now be compared with other results from the experiment, namely direct scattering measurements (such as Ref. 9), and more sophisticated inversion techniques such as simulated annealing (Ref. 6).

Acknowledgements

We are most appreciative of the crew of the NATO Research Vessel *Alliance*, and the dedicated personnel from SACLANTCEN.

The Generic Sonar Model from the US Naval Underwater Warfare Centre is instrumental to our work.

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#517165 (18)

Bottom Reflection Properties by Inversion of Ambient Noise

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Abstract
The vertical directionality of ambient noise is strongly influenced by seabed reflections Therefore geoacoustic parameters can be inferred by inversion of the noise In this new approach, using vertical array measurements, the reflection loss is found directly by comparing the upward with the downward going noise Theory suggests that this simple ratio is, in fact, the power reflection coefficient of the seabed – potentially a function of angle and frequency Modelling and parameter searching are minimised, and the method does not require a detailed knowledge of the noise source distribution The approach can handle stratified environments and is believed to tolerate range-dependence Experimental data have been collected with the 62m VLA at five Mediterranean sites and now one New Jersey Shelf site during the Boundary2001 trial

1. Introduction

A new method of deriving bottom reflection loss from ambient noise [1,2] has been tried at five Mediterranean sites and most recently during Boundary2001 at one site on the New Jersey Shelf It can be shown by ray or flux arguments [1,3,4] that if the wind provides a sheet source (with or without distant shipping) the ratio of down-going to up-going noise at the same angle to the horizontal is simply the bottom power reflection coefficient. This results from the peculiarity of sheet sources that there is no *geometric spreading*, but instead there is a *geometric series* of noise contributions from the surface interaction once per ray cycle The upward path has exactly the same geometric series but with one extra bottom reflection near the receiver Therefore a VLA can measure reflection loss almost directly as a function of angle and frequency From this measurement one can then deduce the geoacoustic parameters (if necessary[1]) by employing a model of plane wave reflection loss, such as OASR [5] or more simply, the formulae in [6] for multiple fluid layers with an underlying solid bottom The only significant effect of refraction is to modify angles according to Snell's law and the sound speeds at the bottom and receiver In this paper we look at the experimental results from two Mediterranean sites and the New Jersey Shelf site Then we demonstrate the correctness of the theory by using OASR and OASN to mimic the complete experiment but at the same time provide a comparison with the first Mediterranean site Finally we discuss strengths and weaknesses

2. Experiments

One of the sites visited in November 2000 during MAPEX2000bis was south of Sicily at the northern end of the Ragusa Ridge, where other measurements [7] suggested there was a sandy bottom The beam response of the central 32 elements (0 5m spacing) of the 62m VLA is shown in Fig 1 The "noise-notch" is evidence of the strong downward refraction

The "up-to-down" ratio is shown in Fig 2 Interpreting this as reflection loss we immediately see the classical interference fringes [6] (indeed these can be seen in the lower part of Fig 1 when we know what to look for) By inspection we can deduce several things, the most obvious of which is the critical angle (about 30°) In this example the fringes are regular in frequency (notwithstanding the experimental limitations discussed in Section 3) which means there must be only two dominant reflectors or boundaries Also the layer separation is directly related to the fringe separation (see later) The strength of the reflectionand the depth of modulationof the fringes provide information about the combined speed and density in the two layers Volume absorption in the sediment will certainly affect the low loss region to the left of the critical angle, but experimentally this region is rather 'shaky' since the up-to-down ratio is so close to unity This site is taken as the example in the numerical study of Section 3

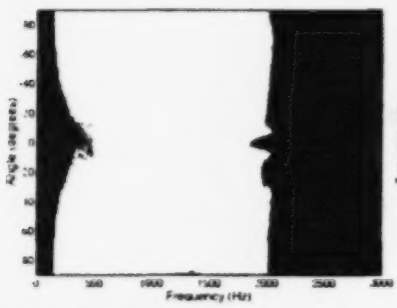

Fig 1 Sicily Sand AR

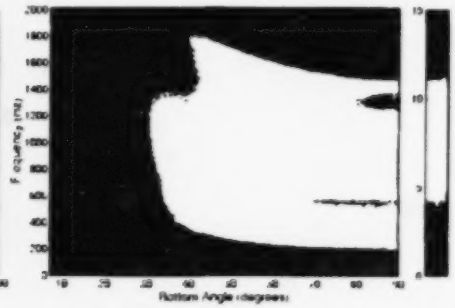

Fig2 Sicily Sand RL

A contrasting site in the same experiment was 'lossy mud' east of Elba This resulted in the reflection loss plot of Fig 3 Here we see evidence of higher losses at low angles, ie an

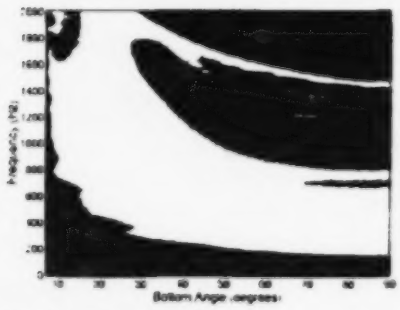

Fig 3 Elba Mud RL

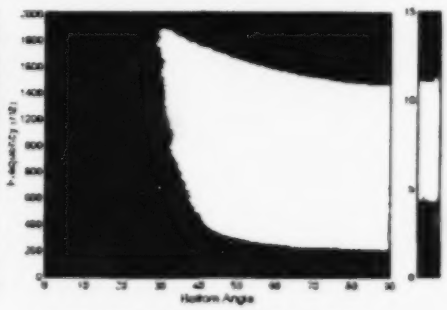

Fig4 NJ Shelf Stiff clay RL

absence of a clear critical angle Also we see two superimposed fringe patterns, one fine – with seven or eight loss maxima visible at. say 90°, and one coarse – with only one

maximum and one minimum visible This suggests three boundaries, two of which are wide apart and two of which are close together It is immediately obvious that one cannot use a simple three layer (ie two boundary) model to explain this data Nevertheless the common assumption of a single sediment layer in more conventional geoacoustic inversion techniques (eg [7]) may be adequate to explain the low loss regime to the left of critical At the New Jersey Shelf site (39°19'N 72°33'W), where we expect a 'stiff clay' [8], we see in Fig 4 a clear critical angle again (about 30°) but either no fringes or complicated ones This suggests many equally weakly reflecting layers, effectively a half-space Note that the apparent frequency-dependence of the critical angle is an artifact explained in the next section

3. Numerical demonstration with OASR and OASN

In a numerical experiment (see more detailed investigation in [9]) it is possible to plot the 'true' plane wave reflection loss for a given bottom environment using OASR [5], and then to calculate the correlation matrix **C** for a vertical array in the noise field of an infinite sheet source above this bottom using OASN [5] We then mimic the inversion technique by first calculating the beam-steered response from the steer vectors as $\mathbf{E}^{\dagger}\mathbf{C}\mathbf{E}$, then dividing 'up' by 'down' We take the environment from [7] with an adjusted layer thickness of 1 3m and isovelocity water (although [9] shows that the SSP is not important) giving the 'true' reflection loss shown in Fig 5 To make the point that the theory is correct we extend the VLA to span the entire water column, but keep the same 0 5m hydrophone separation This noise inversion is shown in Fig 6, and the agreement is almost exact! The main difference is the dark arc at the top caused by the

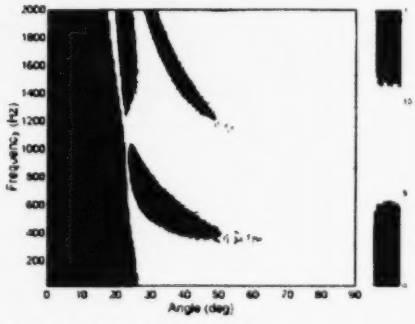

Fig 5 'True' RL (OASR)

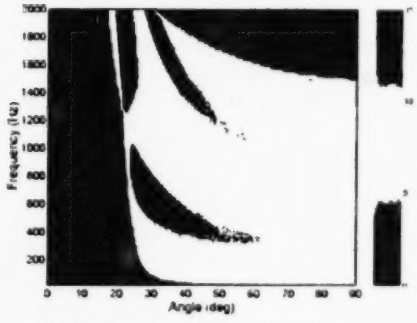

Fig6 Inversion (entire water column)

grating lobe effect visible at bottom right in the experimental plot (Fig 1) The effect of reducing the number of hydrophones to 32, as in the real experiment is shown in Fig 7 As frequency lowers, the beam width widens as was seen in Fig 1 Ultimately the 'up' wide beams see the same thing as the 'down' wide beams, and therefore the degraded reflection coefficient tends to unity, giving the illusion that the critical angle is inversely proportional to frequency Clearly improved beam steering techniques are well worth

pursuing Figure 7 also doubles as a theoretical result to be compared directly with experiment (Fig 1) Agreement is extremely good

4. Conclusions

Having seen plausible site to site variation, and having shown, through numerical experiments that the theory is reliable, we appear to have a robust measurement technique for the direct measurement of reflection loss By inspection and use of a simple plane wave layer reflection model it is possible to convert the loss to useful geoacoustic parameters, such as number of layers, layer thicknesses, sound speeds The awkwardness of using a VLA and the degradation caused by poor angle resolution mean that improved beam steering techniques are well worth pursuing

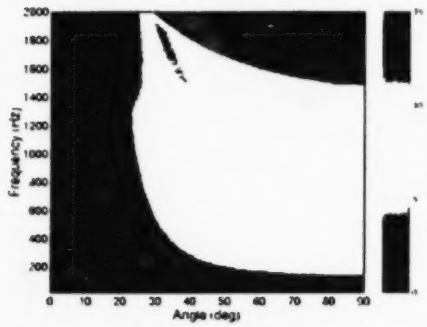

Fig 7 Inversion (short array)

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#517166 (19)

Multistatic Reverberation and System Modelling using SUPREMO

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Abstract

A multistatic sonar performance model, SUPREMO, is being developed at SACLANTCEN. Its capability includes target echoes, reverberation and noise, and operating on simple well-known principles it provides these as a function of delay time and bearing or in equivalent map projection. A modular propagation section makes it possible to separate the difficulties of propagation modelling (ray/mode, range-dependence, . .) from those of scatter-area-accounting in delay-time and bearing (efficiency, bottom slope, scattering law, ...). Several novel trade-offs of efficiency versus approximation are discussed. In the context of Boundary2001 its calculation of reverberation is of most interest. Here we make some comparisons with well-known analytical solutions and Lepage's complementary wave-based model, R-SNAP.

1. Introduction

The idea behind multistatic active sonar is to make use of the many views of the same target against a background of reverberation and noise. However with simultaneous or sequential transmissions many bistatic pairs are possible, each with their own reverberation and problems of interference SUPREMO is a new model designed from the start to handle the extra "housekeeping" in assessing the performance of such a sonar. This paper briefly describes its design and performance. The main structure is in MATLAB which runs the addition-over-scatterers section as a FORTRAN executable The propagation calculations can be run by an external model, if desired. The general philosophy is to allow the user to trade CPU time for approximation in a controlled way (incidentally demonstrating the validity of the approximations) rather than compromising the solution by embedding approximations at the outset. As a result, realistic solutions are available in seconds rather than hours

In the context of the recent Boundary and Geoclutter experiments interest centres on the calculation of bistatic reverberation. Relevant features are summarised as follows. Platforms are assumed to carry an arbitrary numbers of sources and receivers. Each source has a finite bandwidth, a beam pattern, a pulse envelope, and an emission time in an overall repeating sequence. Each receiver has an independent bandwidth and a linear array or beam pattern. The model is designed to be fully range/azimuth-dependent although currently multipath propagation is handled by range-independent codes GAMMARAY [1], PROSIM [2] or an internal image calculation Scattering strength is a function of position and local angles, and the effect of local bottom slope on scattering can be included.

At a high level the program structure is very simple. First the propagation from each source and *from* each receiver location is tabulated. Then for each possible bistatic pair a target calculation and a reverberation calculation (bottom, surface and volume) result in total echo strength versus absolute time (or delay time relative to any particular source) For each receiver there will eventually be an ambient noise calculation based on wind, known local ships and a shipping background. Finally one can generate displays in all the standard forms, and some are shown later. Naturally the display for each source/receiver combination may include interfering contributions from the other sources; this is precisely the novelty of multistatic assessment.

2. Propagation

Whether the external propagation model is range dependent or independent it must supply a set of intensities I_n, elevation angles θ_n, and delay times t_n for each range (and bearing). The set can consist of strict eigenrays or just sampled intensity. Conversion work is required for wave models These three parameters are tabulated non-linearly against range to allow for more detailed representation at close range. In anticipation of the scattering calculation, where scattering strength is a separable function of angle-in and angle-out, a table of 'modified intensity', eg $I_n \times \sin(\theta_n)$ is also built

A crucial fidelity issue is the inclusion, for each scatterer, of all combinations of eigenrays-in and eigenrays-out. To retain fidelity but avoid excessive CPU times it is possible to 're-sample' the eigenrays whilst keeping the total energy unchanged. Regarding them as a continuous function of time and angle they can be sampled progressively more coarsely, at the user's discretion. In this way one can see whether the extra fidelity was really justified.

3. Reverberation

Here we concentrate on bottom reverberation although surface and volume modules function in a similar fashion. There are three calculation stages, as follows:

• *Stage 1: Pre-process Scatterers*

In principle, numerical scatterers can be regarded as points or contiguous rectangular or triangular facets. Only the rectangles are forced to be on a grid. The model takes its scatterers from a list (in any order) giving, for each scatterer, x,y location and product of facet area times local (interpolated) scattering strength. However the user always defines scattering strengths at the intersection points of a rectangular grid. One user-option is to define scatterer locations as the same grid points. Although area accounting is correct, there is a reverberation sampling problem; at long range there is an unnecessarily large number of weak scatterer contributions (computational overkill), and at short range an unacceptibly small number of strong scatterers (spiky artifacts). What we really want is a uniform density of scatter contributions in time-bearing space One way (of several) of doing this is to set up a uniform random distribution of points in time-bearing space then map them back to the seabed using a crude horizontal plane transformation Taking these dots as the starting point we join them with Delaunay triangles to form a surface of

triangular facets (Fig 1, note concentration near receiver (10,10)) We then calculate x,y for each facet centre, and the product of facet area and interpolated scattering strength

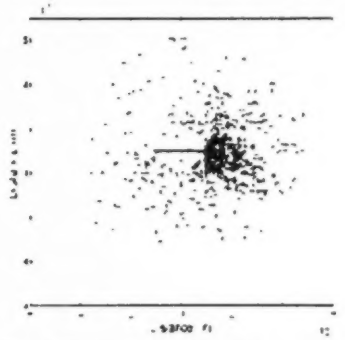

Fig. 1 Delaunay triangular scatterers. Note concentration at r4eceiver

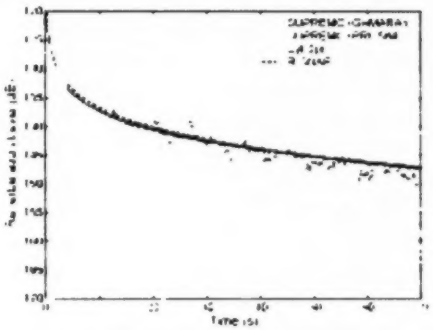

Fig. 2 Comparison with R-SNAP and cylindrical spreading

Although a new calculation is required for each source/receiver combination the entire operation takes only a fraction of a second for several thousand scatterers, and therefore CPU time is quite negligible The effect on time-bearing is, at worst, a superimposed weak random ripple spanning all ranges Of course this is merely a numerical device and any required spatial detail must be resolved by the scattering strength grid

• *Stage 2 Calculate scatterer contributions. Allocate to time-bearing bins*

Given the revised set of 'eigenrays' and the scatterer list the model gets the intensity contribution from every combination of scatterer, eigenray-in and eigenray-out as $I_n \times I_m \times S_i(\theta_n , \theta_m , \beta) \times A_i$, where the (linear) separable scattering strength of the ith facet is $S_i(\theta_n,\theta_m,\beta) = S_{IN}(\theta_n) \times S_{OUT}(\theta_m) \times S_{BIS}(\beta) \times F_i$, and its area is A_i The arrival bearing and elevation angle are converted to equivalent beam angle α at the receiving array Since the round-trip travel time is known the intensity contribution can be added to the appropriate time-bearing bin The result is a reverberation intensity array versus time and bearing

• *Stage 3 Post-process in time-bearing space*

If we had used a rectangular pulse of the same length as the *time* bin separation and rectangular beams of the same width as the *angle* bin separation the allocated scattering area would be exactly correct (Note that for a linear array we need bin width proportional to $\sin(\alpha)$) For other cases we need to compensate in both time and angle, here we discuss time only Suppose we use very fine bins, so that we frequently find empty ones With appropriate normalisation we can find the response to any pulse (envelope) shape by convolution We do this in the frequency domain as a post-process by storing the FT of the desired pulse, multiplying by the FFT of the reverberation and then IFFTing back to time For each source/receiver pair this extra FFT and IFFT only

needs to be done once after all reverberation and target contributions have been inserted into the master array It therefore takes a negligible time since it is always much faster than any of the acoustic calculations Note that high time resolution is only required at the leading edge of the reverberation and for rapidly varying scatter features (ie "geo-clutter"). A future variant of this process will allow the combination of low resolution "diffuse" reverberation and high resolution "geo-clutter" to maximise efficiency

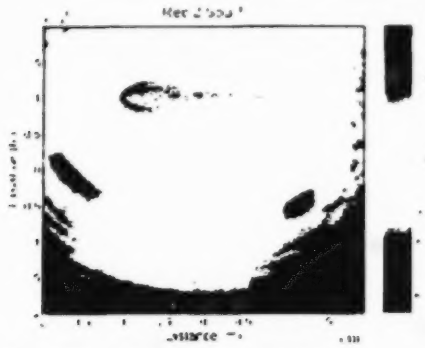

Fig. 3 Geo-plot: Receiver at (10,10), Source at (-10,10) (km)

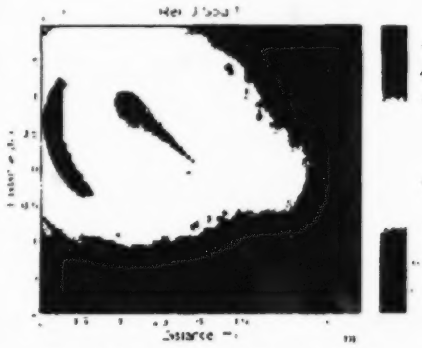

Fig. 4 Geo-plot: Receiver at (0,0), Source at (-10,10) (km

Some preliminary comparisons of reverberation are shown in Fig 2 using SUPREMO + GAMMARAY (blue), SUPREMO + PROSIM (green), (incoherent) R-SNAP [3] (red), and cylindrical spreading (black) Agreement is good Finally Figs 3,4 show some examples of geographic plots for a source at (-10.10) and a receiver at respectively (10,10), corresponding to Fig1, and (0,0)

4. Conclusions

SUPREMO is a versatile new multistatic reverberation model capable of producing plots comparable with those of the Boundary experiments. Geoclutter and separate multipath arrivals can also be modelled However phenomena as complex as buried river channels can only be included as a local change in scattering strength It is hoped that more direct comparisons will be made during the next Boundary experiment

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Reverberation modeling for complex environments

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1. Introduction

The modeling of reverberation in areas characterized by high-resolution environmental measurements places demands on the ability of the models to accept these environmental inputs Typical environmental characterizations might include high-resolution bottom and subbottom bathymetry and site measurements of the geo-acoustic and commensurate reflecting and scattering properties of the seafloor At SACLANTCEN there has been a modeling program underway for the last four years directed towards building better reverberation models, models which are based on wave theory and which are capable of incorporating detailed environmental information The R-SNAP and BiStaR models are the results of this modeling effort R-SNAP is a monostatic range dependent reverberation model [2] which uses SACLANTCEN's C-SNAP coupled normal mode code as a range dependent Green function generator and a coherent reverberation theory [1] to predict monostatic reverberation in well characterized range dependent environments BiStaR, which is still under development, is the bistatic extension to R-SNAP, and subsumes the R-SNAP functionality for horizontally monostatic source-receiver geometries

2. Boundary/Geoclutter high resolution environmental characterizations

The Geoclutter/Boundary series of reverberation experiments have a large amount of supporting environmental information, both in the form of high resolution bathymetric and subbottom geophysical survey type measurements and spot surveys of the underlying geoacoustic, reflection and scattering properties of the seafloor The high resolution bathymetry collected in the vicinity of the Ragusa ridge (a significant scattering feature) on the Malta plateau by SACLANTCEN during the Boundary 1999 and 2000 experiments is shown in Fig 1, and the same type of survey collected at the Geoclutter/Boundary 2001 site on the New Jersey shelf by UTIG is shown in Fig 2 [3] Corresponding subbottom profiles also have been collected for these two sites [4,5], and in the case of the New Jersey shelf additional high resolution seismic profiles are still being collected. The bottom reflection and scattering measurements have been collected for both sites by Holland and have been reported for the Malta plateau and other Mediterranean sites [6,7]

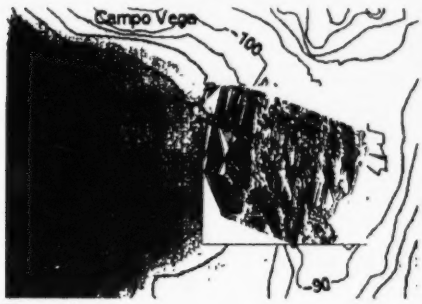

Figure 1.

Figure 2.

3. SACLANTCEN models

The R-SNAP model is a coherent reverberation model which can describe scattering from on or within a range dependent seafloor The Green function to and from the scatterers is modeled with coupled modes and the transformation from the frequency to the time domain is handled using range dependent group speed concepts which are superior to the adiabatic approximation [8,9] Fig 3 is a four panel plot which shows from top to bottom. the incoherent TL onto the Ragusa ridge at 630 Hz, the corresponding range dependent model amplitudes in dB, the range dependent scattering kernel SS, and the R-SNAP RL estimate for seafloor scattering with a Lambert coefficient of –27 dB In Figs. 4a and 4b the measured and predicted monostatic reverberation from the Malta plateau feature seen from site C2 (Fig 1) are shown side by side The measured data were supplied by John Preston of PSU Here the "Rapid REA" seafloor properties derived for the Malta Plateau by Preston and Ellis [10] have been used in conjunction with the high resolution bathymetry and seabed characterizations to obtain the prediction

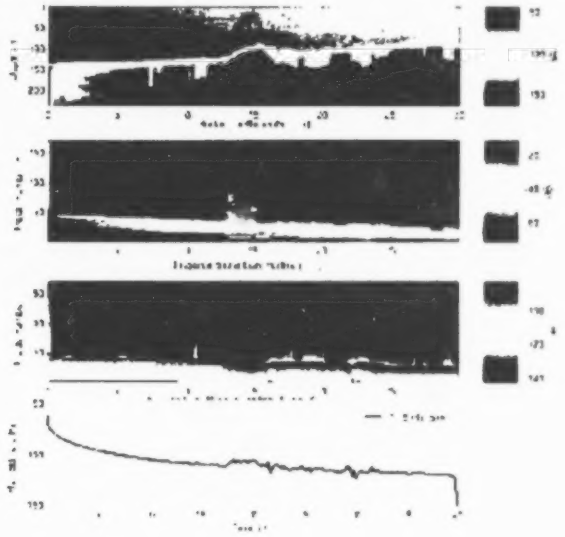

Figure 3.

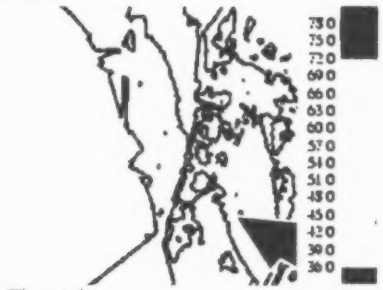

Figure 4a.

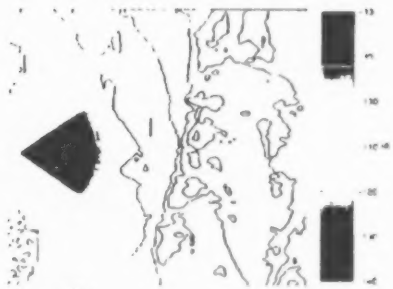

Figure 4b.

4. Modeling reverberation from buried features

The Geoclutter/Boundary 2001 site has been observed to have a significant number of clutter features which do not seem to be strongly correlated with the relief of the sediment/water interface [11]. The fundamental hypothesis advanced by Makris and Goff is that buried river channels may be a contributing mechanism to clutter in the Geoclutter/Boundary 2001 test site. Here we evaluate reverberation from the notional buried river channel shown in blue on Fig. 2.

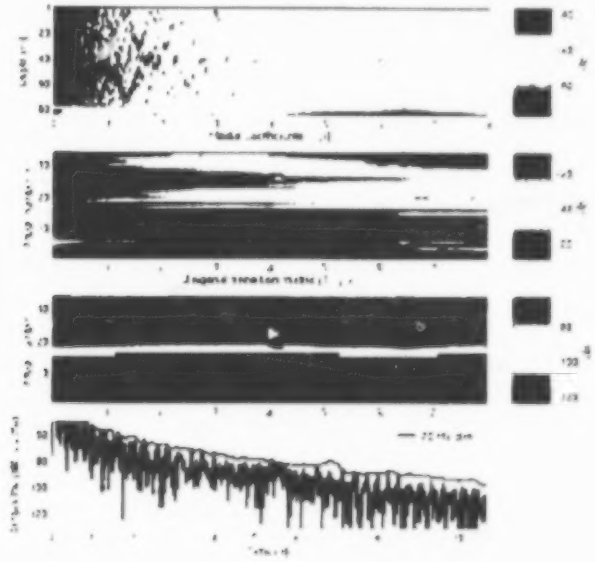

Figure 5.

In Fig. 5 a four panel plot is shown for propagation and scattering from a 2 m deep channel buried beneath 5 m of sediment. The sediment properties themselves are assumed to be those of notional sand, with a density of 1.7 gm/cm^3 and a sound speed of 1600 m/s. As discussed in Makris and Ratilal [12], the properties of the overlying sediment are critical to the ability of the buried feature to be ensonified. Here we also see that the range dependence of the relief of the sediment basement interface at the buried channel allows a sediment resonance to be excited at the channel range. The proper excitation of this resonance is critical to the proper modeling of the reverb from this feature, and the R-SNAP model properly treats the range dependent propagation over the channel relief for this case. In Fig. 6 a monostatic reverberation rose for scattering from the same river channel shows that the apparent range of the channel appears greater than the true range due to the low speed of the high order modes which excite it.

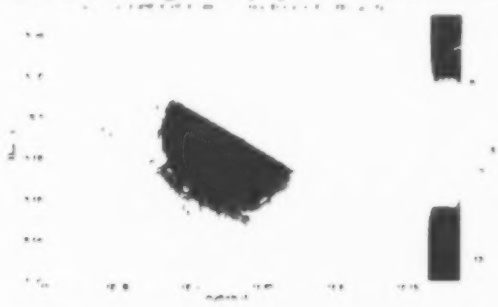

Figure 6.

5. Modeling reverberation from the New Jersey shelf break

A second feature in the reverberation from the Geoclutter/Boundary 2001 test site was the higher then expected returns from the shelf break. Figure 7 shows in black reverberation data for a downslope beam over the shelf break supplied by John Preston of PSU. A range independent reverberation prediction is overlaid in red, and a range dependent R-SNAP prediction is overlaid in blue. The range dependent prediction shows that there is reduced reverberation over the shelf break, in contradiction to the observations. One hypothesis which may account for the increase in reverb over the shelf break is that the sides of the canyons are rougher. The dashed blue line in Figure 7 shows that the shape of the R-SNAP reverberation prediction for the downslope portion of the shelf break agrees quite well with the observations if a higher scattering strength is used

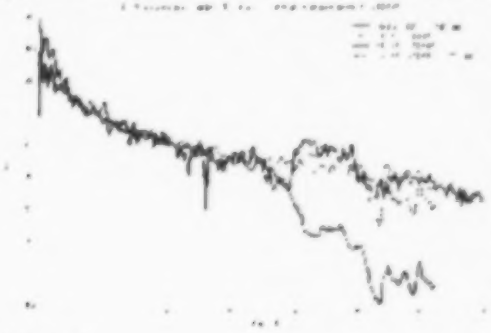

Figure 7.

5. Conclusions

The R-SNAP model has been exercised to investigate enhancements in scattering from the Ragusa ridge on the Malta plateau, and from buried river channels and the shelf break at the New Jersey Geoclutter/Boundary 2001 test site. In all three cases the ability of the model to accept high resolution environmental information was critical to the ability of predict enhancements to the reverberation. In the case of the Ragusa ridge, the shoaling basement depth provided by subbottom profiling was the dominant mechanism for enhanced reverberation. In the case of the buried river channels, the presence of the river channel proved important for the excitation of a sediment resonance which was mainly responsible for the reverberation enhancement. For the shelf break environment, the ability of the model to treat downslope propagation to and from the canyon walls proved important for modeling the structure, if not the amplitude, of the observed reverberation enhancement.

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In April-May 2001, consecutive sea trials were conducted at two well characterized shallow water sites off of North America's east coast – the Strataform site off the coast of New Jersey and Scotian Shelf off the coast of Nova Scotia. The trials were in support of two distinct but related research programs referred to respectively as GeoClutter and Boundary Characterization.

The focus for GeoClutter is to develop a methodology for identifying and classifying false targets (in the ASW context) present in littoral waters. These false targets typically occur when Low Frequency Active (LFA) sonars measure strong coherent returns from the seabed at locations where bathymetric maps indicate benign bottoms. This frequently occurs in littoral waters where, for example, ancient river channels are overlaid with soft sediment. The high-frequency systems employed to measure bathymetry are unable to penetrate the seabed so that these complex sub-bottom features go unnoticed.

Boundary Characterization seeks to enhance active sonar design as well as performance prediction capabilities in littoral waters by statistically characterizing the effects of the complex seafloor and sea surface on broadband scattering and propagation of sound. The principal focus of the project is the development of techniques to measure the environmental parameters that control diffuse reverberation in the low kiloHertz band.

For the purpose of experimental efficiency and because there is significant overlap in the objectives of the two programs, several assets and many personnel participated in both trials. To maintain the momentum of the collaboration and focus the data analysis and modeling efforts, a symposium style workshop was held at DREA in October 2001. The focus of this workshop-symposium was to present an overview of the two sea trials as well as present initial measured and modeled results. Preliminary results indicate that (1) littoral water GeoClutter will cause significant false target reports in present and future LFA systems if it is not addressed. This will require a balanced approach combining fundamental at-sea measurements with signal processing techniques aimed at separating Geoclutter from true targets. (2) The Boundary Characterization program is leading to a much better understanding of the seabed and sea surface and their effect on propagation and scattering of sonar signals. This information will be used to validate and improve Rapid Environmental Assessment (REA) techniques and optimize the performance of multistatic active sonar systems by exploiting environmental knowledge.

Representatives from Defence Research Establishment Atlantic (DREA), SACLANT Center, the US Office of Naval Research (ONR), and the Naval Research Laboratory (NRL), Naval Undersea Warfare Center (NUWC), Massachusetts Institute of Technology (MIT), the Pennsylvania St. University Applied Research Laboratory (PSU ARL), the University of Texas, and the University of Colorado contributed oral and written papers. This proceedings contains the papers contributed to the symposium.

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